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## Phenotypic plasticity and genetic adaptation of plant functional traits on global scales

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## CHAPTER 2

# Global analysis of trait-trait relationships within and between species

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## Summary

- Some robust trait-trait relationships between species, including the leaf economic spectrum (LES), are regarded as important plant strategies but whether these relationships represent plant strategies in reality remains unclear.
- We propose a novel approach to distinguish trait-trait relationships between species that may represent plant strategies *vs.* those relationships that are due to common drivers, by comparing the direction and strength of intraspecific trait variation (ITV) *vs.* interspecific trait variation. We applied this framework using a unique global ITV database we compiled, which included eleven traits related to LES, size and roots, and observations from 2064 species occurring in 1068 communities across 19 countries.
- Generally, compared to between species, trait-trait relationships within species were much weaker or totally disappeared. Almost only within the LES traits, the between-species trait-trait relationships were translated into positive relationships within-species, which suggests they may represent plant strategies.
- Moreover, the frequent coincidental trait-trait relationships between species, driven by co-varying common drivers, imply that in future research, decoupling of trait-trait relationships should be seriously considered in model projections of ecosystem functioning. Our study emphasises the importance of describing the mechanisms behind trait-trait relationships, both between and within species, to deepen our understanding of general plant strategies.

**Key words:** common environmental drivers, global meta-analysis, interspecific trait variation, intraspecific trait variation, plant strategies, trait-trait relationships

## 2.1 Introduction

Despite widely recognised trait-trait relationships between plant species, including plant trait correlations that define the so-called global leaf economics spectrum (LES), it remains unclear whether these economics spectra represent true coordination or trade-offs (Grubb, 2016). LES describes the multivariate relationships between six leaf traits (leaf mass per area (LMA), photosynthetic assimilation rates ( $A_{\text{mass}}$  or  $A_{\text{area}}$ ), leaf nitrogen (N), leaf phosphorus (P), dark respiration rate ( $R_{\text{mass}}$  or  $R_{\text{area}}$ ), and leaf lifespan (LL)) and runs from a fast to a slow return of plant leaf investment among species (Wright *et al.*, 2004; Westoby *et al.*, 2013). LES has been suggested to represent plant strategies, and it has been variably extended to include other plant organs such as stem economics spectrum (SES), root economics spectrum (RES), and even to a whole plant economics spectrum (PES) (Freschet *et al.*, 2010; Reich, 2014). If trait relationships arise through physiological mechanisms or eco-evolutionary constraints and thus represent plant strategies, these trait relationships can help, for example, predict how plants respond to projected changes in future climatic conditions. However, other underlying or confounding causes may give rise to similar trait relationships without representing plant strategies and without resulting in predictive patterns. To date, it remains unknown whether economics spectra reflect plant strategies in reality (see **Box 1** for terminology and definitions).

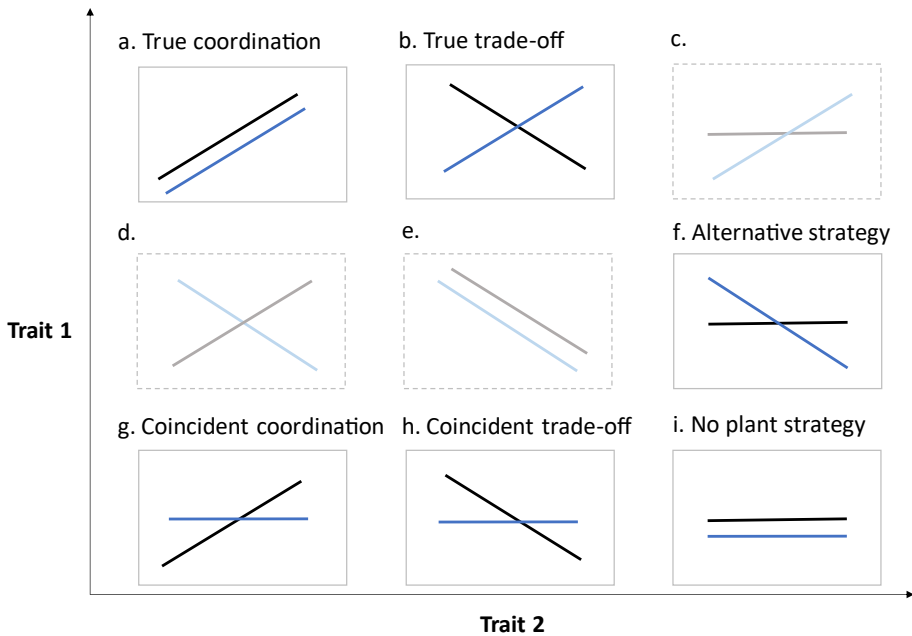
Some studies argued to disregard LES as general plant strategies. For instance, Osnas *et al.*, (2013) suggested that some of the strong correlations among above-mentioned six LES traits might be induced by mass normalisation and thus might not represent plant strategies (Lloyd *et al.*, 2013), while Westoby *et al.* (2013) and Poorter *et al.* (2014) emphasized the value of those mass-based LES traits from a carbon investment perspective. Edwards *et al.* (2014) also questioned if the so-called LES trade-off actually constitutes generic evolutionary trajectories of those traits as they did not find a correlation between LL and LMA in deciduous species. Moreover, both Dwyer & Laughlin (2017) and a meta-analysis by Zeballos *et al.* (2017) found that the correlation between plant traits was context-dependent and that stressful climatic conditions strengthened this relationship. While this phenomenon may indicate an eco-evolutionary constraint, it may also indicate trait convergence of two otherwise independent traits under the influence of a common driver. Given that water and nutrient availability affect most LES traits, the availability of these resources may act as a common environmental driver that leads to trait correlation without necessarily representing a plant strategy.

Other studies interpreted LES as plant strategies by proposing physiological and eco-evolutionary mechanisms and evidence for these LES trait-trait relationships. For example, Shipley *et al.* (2006) proposed that the LES could be explained by a fundamental trade-off between allocation of plant resources to structural tissues or leaf photosynthetic processes. More recently, Onoda *et al.* (2017) provided physiological and structural support for this assumption in a meta-analysis based on anatomical and other rarely measured traits. They found that long leaf lifespans were achieved by higher LMA and in turn by a higher cell wall mass fraction, which inevitably reduced photosynthetic efficiency. In addition, from an eco-evolutionary point of view, Donovan *et al.* (2011) argued that most of the trait concordance may be caused by selection, which leads to the elimination of low fitness individuals with those leaf trait combinations that function poorly in given biotic and abiotic conditions.

Although extensive research about plant strategies has been done, most studies have focused on trait relationships resulting from interspecific variation. Instead, by assessing trait correlations for both intraspecific and interspecific variation, it can be discerned whether LES (PES, or any trait-trait relationship) represents a plant strategy or is a coincidental relationship unlikely to be associated directly to a strategy. Assuming that the LES or PES spectra arise through physiological mechanisms or eco-evolutionary constraints, one would expect that the trait-trait relationships observed between species also exist within species. If so, these within-species relationships should express themselves through the relationships of intraspecific trait variation (ITV) among traits, because ITV can be considered as a plant strategy characteristic. Compared with between-species trait-trait relationships, ITV is likely to better reflect trade-offs between traits based on resource allocation constraints. Because, for example, within an individual plant, investing available resources into one trait would directly constrain the investment of remaining resources to other traits (Eichenberg *et al.*, 2015). Evaluating the ITV relationships among traits is therefore likely a more direct assessment of the physiological mechanisms or eco-evolutionary constraints driving trait correlation than assessing the relationships between species alone, for which the likelihood of confounding factors (such as common drivers or differences in habitats) is larger. However, the evidence for trait-trait relationships within species is limited, and most studies only assessed a small number of species (*e.g.* Niinemets, 2015; Martin *et al.*, 2017). The only large-scale analysis (39 paired species for ITV) so far (Anderegg *et al.*, 2018) found mixed evidence for the existence of LES trait correlation within species.

The objective of this paper was to assess whether LES (as well as some PES trait relationships) are plant strategies by comparing the direction and strength of trait-trait relationships within species and between species in a global meta-analysis. In this study, we used the slope of the within-species trait variation *vs.* the community trait variation as a measure of ITV (Ackerly & Cornwell, 2007; Lepš *et al.*, 2011). Similar to alternative measures of ITV (*e.g.* the coefficient of variation), this metric is unit-less and thus aids comparison across traits. However, in contrast to alternatives, our metric is not affected by the length of the environmental gradient that is studied nor the absolute variation in trait values, and these influences will therefore not bias reported estimates of ITV or its covariation.

We propose a conceptual framework that illustrates how different relationships (positive, negative and none) in interspecific trait variation translate into a possible correlation of ITVs. Assuming that physiological mechanisms or eco-evolutionary constraints drive both within and between trait-trait relationships, we can compare these relationships to discern between plant strategies and coincident relationships (**Fig. 2.1**, see also **Box 2.1** for terminology and definitions). In the case of a plant strategy across species, we will observe either positive or negative trait-trait relationships between species means, combined with a positive ITV coordination across species (the variability of the traits within species is positively correlated, which means plants change both traits at the same time; **Fig. 2.1a,b**). This implies that negative ITV correlations (suggesting that high within-species variation within one trait coincides with low within-species variation in another trait) driven by physiological mechanisms or eco-evolutionary constraints across scales should not exist (**Fig. 2.1d,e**). If species deal with environmental pressures by alternative adaptation strategies, and thus change either one or another trait, then we would expect to see no relationship between these two traits across species but a negative correlation in ITV (**Fig. 2.1f**). Consequently, **Fig. 2.1c** should not exist. If the trait correlation that is observed between species is strongly caused by common drivers, then there would be no strong correlation between ITVs (**Fig. 2.1g,h**). **Fig. 2.1i** shows if there is no trait correlation between species because of the absence of a corresponding plant strategy, then we will not observe trait-trait relationship within species either. We evaluated our framework by compiling and analysing a global database of multiple trait data of 2064 species from 19 studies.



**Figure 2.1** Hypothetical trait-trait relationships between species (showing interspecific trait variation, in black) and within species (showing intraspecific trait variation (ITV), in blue), *a.* True coordination, positive trait-trait relationships both between and within species. *b.* True trade-off, negative trait-trait relationship between species but positive within species. Both true coordination and trade-off are considered as plant strategies. *c., d. and e.* do not exist according to our hypotheses. *f.* Dominance of alternative strategies, either of the two traits is adapted at a given situation to deal with an environmental pressure. *g.* Coincident coordination, positive trait-trait relationships between species but no relationships within species. *h.* Coincident trade-off, leading to negative trait-trait relationships between species but no relationships within species. *i.* No plant strategy involved in the assessed traits, no trait-trait relationship neither between nor within species. See Box 1 for more details on definitions and terminology.

### Box 2.1 Definitions of terms used in this study and mechanisms behind our framework

**Plant strategy:** There are many different definitions of plant strategies, but all describe how species respond to their environment and recognise that plants have a finite set of resources allocated in different ways to growth, reproduction, and maintenance. Functional trait-based strategies relate to a set of different trait values, expressing the investment of individuals to optimise their fitness in a given environment. In this study, we focus on relationships between two traits. Relationships between traits of different species can show a lack of a significant correlation, a positive correlation (“**coordination**”) or a negative correlation (“**trade-off**”).

An **apparent** significant **coordination** or **trade-off** between two traits of different species may be caused by three mechanisms:

1. **Physiological mechanism**, describes the situation in which two correlated traits, because they are linked through chemical and physical plant functions, are limited to a range of values that they can attain. For example, the trade-off between seed quantity and seed mass with species having either a high number of small seeds or a limited number of large seeds because of carbon limitations. Physiological mechanisms lead to “**true trade-offs**” and “**true coordination**”. This also includes mathematical dependence among traits, which express physiological dependencies, such as among structural LES traits (see eq. 2.4 in main text). We use the word “true” throughout to refer to trade-offs and coordination where the change of a trait will result in a change of another trait (*sensu* Grubb 2016), merely in contrast to “coincident” relationships, that describe traits that co-vary through a common confounding driver (mechanism 3 below).
2. **Eco-evolutionary constraint**, describes ecological and evolutionary processes that affect the fitness of species, ultimately resulting in the evolution of particular plant strategies. This includes **phylogenetic constraint** (where possible combinations of trait values have not evolved in a lineage. For example, nitrogen fixation being constrained to legumes), and **ecological constraint** (where trait combinations are physiologically possible, but lead to lower fitness, which results in the trait combinations being outcompeted, and thus not leading to an evolutionary stable strategy. Given that our definitions of coordination and trade-offs do not imply costs, eco-evolutionary constraints can lead to both “**true coordination**” and “**true trade-off**”. Multiple evolutionary stable strategies may be present in a single environment, due to multiple eco-evolutionary constraints act simultaneously, each representing an alternative functional design of approximately equal competence (Marks & Lechowicz, 2006). Such situations may conceal a “**true coordination**” and “**true trade-off**”.
3. **Common driver impact**, describes a coincident trait-trait relationship that exists due to a common environmental driver, which drives the variation of two traits independently without necessarily involving a physiological or eco-evolutionary mechanism that links the two traits. This results in an apparent between-species trait-trait relationship in this study, either “**coincident coordination**” or “**coincident trade-off**”.

**Plant strategies** are represented by “true coordination” and “true trade-offs” between traits. It is conceptually important to separate the two mechanisms that create these patterns (numbers 1 and 2 above), as they have different implications. However, since physiological and eco-evolutionary mechanisms cannot yet be separated empirically, they have been combined in our framework. Using this framework (Fig. 2.1), we can distinguish plant strategies from coincident relationships. To do so, we jointly assess inter-specific trait-trait relationships and the relationships between intraspecific trait variation (**ITV**) of those same traits. **ITV-ITV** relationships represent the trait-trait relationships of intraspecific trait variation, which is equivalent to trait-trait relationships within species.



## 2.2 Materials and Methods

### 2.2.1 Database preparation

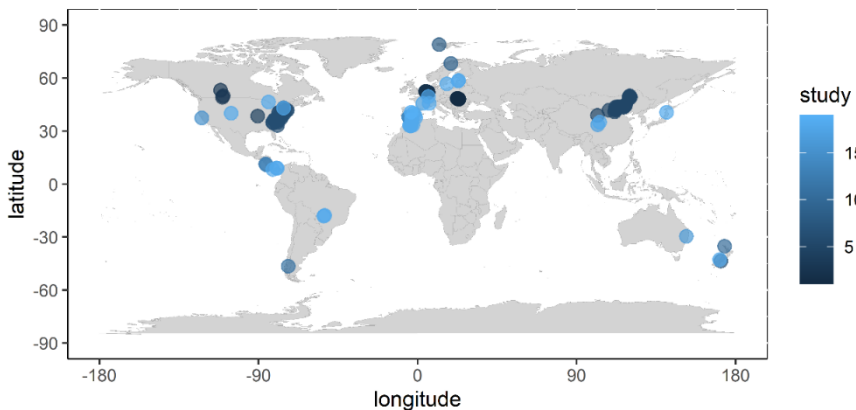
To test our framework, we prepared a global database of intraspecific variation (ITV) of multiple traits in four steps. Firstly, we collated published and unpublished datasets for inclusion in a trait database for analysis of ITV. Data were obtained from three sources: unpublished datasets from our previous and current research projects; published data from supplementary materials or public databases where datasets had been deposited; and original datasets of published articles which were provided directly by the authors. To obtain data from the latter sources, we searched Google Scholar using various combinations of the following keywords: plasticity, intraspecific trait variation, intraspecific trait (variation or variability), individual trait, trait gradient analysis, Ackerly & Cornwell and Lepš. For resulting studies, we evaluated whether the paper as well as its associated data contained the following information: 1) a list of plots (or communities); 2) a list of species sampled in those plots with at least one species occurring in three or more plots; 3) a list of plot-mean trait values or individual trait values measured for sampled species in each plot; 4) a list of abundances for each species in each plot (or species richness data of individual plots to allow estimating species abundance). If all these four criteria were met, available data were downloaded or authors were contacted for provision of their trait data or complementary data (*e.g.* abundance data). We also searched published datasets deposited in the Dryad Digital Repository (<https://datadryad.org/search>) by using the following keywords individual trait, intraspecific trait. Our trait database was compiled from 17 resulting studies (Ordoñez *et al.*, 2010; Kembel & Cahill, 2011; Kichenin *et al.*, 2013; Siefert *et al.*, 2014; Carmona *et al.*, 2015; Jager *et al.*, 2015; Buzzard *et al.*, 2016; Cheng *et al.*, 2016; de la Riva *et al.*, 2016; Spasojevic *et al.*, 2016; Derroire *et al.*, 2018; Li *et al.*, 2018; Fajardo & Siefert, 2019; Niu *et al.*, 2020; E. de Goede *et al.*, unpublished (2 datasets); P. M. van Bodegom *et al.*, unpublished; for more details, please see Supporting Information Table S1).

Secondly, we cleaned the data, by removing observations of taxa that had not been classified to species level, omitting observations on mosses, lichens, clubmosses and succulents, and updating species names to accepted names according to The Plant List (<http://www.theplantlist.org/>) using the R package *Taxonstand* (Cayuela *et al.*, 2012). Moreover, we ensured that units of each trait were consistent and created unique plot IDs. We unified the abundance of all studies to relative abundance so that the sum of abundances of all species in each plot was 100 per

cent. For four studies that provided individual records rather than abundance, we calculated their relative abundance from the number of individuals of each species in the plot divided by the total number of individuals in the plot (Supporting Information Table S1). All trait data were measured in the field, and predominantly on adult individuals. However, a limited number of observations relate to seedlings from tree species. To reduce any ontogenetic bias, we excluded any maximum height observations of tree seedlings from the database.

Thirdly, for each species and each trait in our database, we calculated the magnitude of ITV and species mean trait value using trait-gradient analysis (Ackerly & Cornwell (2007), see section 2.2) and compiled them into a new dataset, together with two datasets (Study 15&16 in Table S1) that already contained 120 species' ITVs and species mean trait values derived from the trait-gradient analysis (Ackerly & Cornwell, 2007; Kooyman *et al.*, 2010).

Fourthly, traits which had data from at least four studies were selected, resulting in a dataset of 11 functional traits, namely specific leaf area (SLA), leaf size (LS), leaf dry matter content (LDMC), leaf nitrogen content (LNC), maximum height (MH), leaf phosphorus content (LPC), leaf carbon content (LCC), leaf thickness (Lth), leaf tissue density (Ltis), stem specific density (SSD), and specific root length (SRL). In total, the final ITV database contained 2064 species (Supporting Information Table S2) and these observations came from 1068 communities (plots) across 19 countries covering tropical, temperate and boreal biomes (Fig. 2.2, Supporting Information Table S1).



**Figure 2.2** Site/plot locations of 19 studies which were compiled in our global species' intraspecific trait variation database. Some studies contained multiple sites. Those locations were marked in the same colour for each study.

### 2.2.2 Defining intraspecific trait variation using trait-gradient analysis

We defined and determined estimates of ITV using the trait-gradient analysis, as outlined by Ackerly & Cornwell (2007).

The plot mean trait value,  $\overline{p}_j$ , can be mathematically expressed as:

$$\overline{p}_j = \frac{\sum_{i=1}^S a_{ij} t_{ij}}{\sum_{i=1}^S a_{ij}} \quad (\text{eq 2.1})$$

Where  $\overline{p}_j$ , is defined as the abundance-weighted mean trait value across all species in plot  $j$ . Given that traits may be considered to converge under the influence of environmental pressures, this value represents the position of a plot along the environmental gradient driving this trait (Ackerly & Cornwell, 2007).  $t_{ij}$  is the individual species trait value of species  $i$  in plot  $j$ ,  $a_{ij}$  is the abundance of species  $i$  in plot  $j$ , and  $S$  is the total number of species in plot  $j$ .

The species mean trait value  $\overline{t}_i$  was calculated as:

$$\overline{t}_i = \frac{\sum_{j=1}^P a_{ij} t_{ij}}{\sum_{j=1}^P a_{ij}} \quad (\text{eq 2.2})$$

with  $P$  being the total number of plots where this species occurs. The between-species trait-trait relationships presented in this study refer to relationships between species mean trait values.

In addition to calculating ITV (explained below) and species mean trait values, this method also allows determining species niche breadth,  $R_i$ , which is defined as the range of  $\overline{p}_j$  that species  $i$  occupies along the trait gradient. It is calculated as:

$$R_i = \max(\overline{p}_j) - \min(\overline{p}_j) \quad (\text{eq 2.3})$$

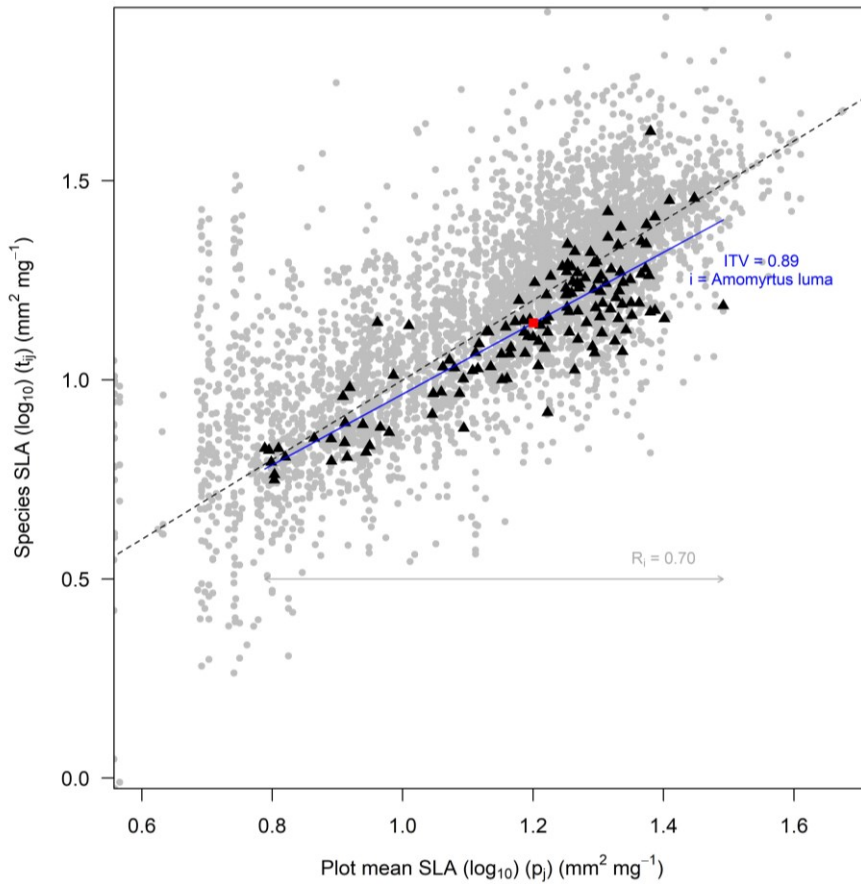
The trait-gradient analysis expresses ITV relative to the (community-weighted) trait variation in the community. If one visualizes the variation of individual species trait values  $t_{ij}$  vs. the plot mean trait values  $\overline{p}_j$  (**Fig. 2.3**), sets of points (grey dots) align vertically at a particular value of  $\overline{p}_j$ , which indicate the species that co-occur in the same plot  $j$ . A weighted least squares (WLS) regression through all  $t_{ij}$  vs.  $\overline{p}_j$  represents the community trait variation which, by definition, falls on a 1:1 line (represented in **Fig. 2.3** by the black dashed line). For an individual species, the slope of the WLS regression line of  $t_{ij}$  vs.  $\overline{p}_j$  for that species reflects the magnitude of ITV of that species relative to the community trait variation. **Fig. 2.3** shows an example of the WLS regression for the species *Amomyrtus luma* (Molina) D.

Legrand & Kausel represented by 134 SLA observations in our global database, weighing each point by plot abundance.

Thus, we express ITV as a slope, instead of expressing intraspecific variation as a percentage of the mean trait value of a given species (*e.g.* Albert *et al.*, 2010a; Messier *et al.*, 2010; Violle *et al.*, 2012) The range over which a species' trait varies is likely to increase with an increase in length of the environmental gradient, which renders the latter approach sensitive to the length of the gradient. Instead, expressing ITV as a slope is much less affected by the length of the environmental gradient for which observations of an individual species are available. At the same time, like other metrics, our ITV metric is unit-less and thus it allows direct comparison across traits.

We repeated the trait-gradient analysis procedure to calculate ITVs and species mean trait values for all eleven traits. For most traits, except for LDMC, LCC and SSD, their original trait values did not conform to a normal distribution, thus their  $\log_{10}$ -transformed trait values were used in these calculations.

Before testing our hypotheses, we scrutinized the robustness of the ITV values in our database. Firstly, we omitted those species for which estimates of ITV were associated with a large estimation error ( $SE > 1$ ; our results were robust to choices in the SE threshold according to a sensitivity analysis, see Fig. S1-2 in Supporting Information). Since slope estimates based on two points are not reliable, we also excluded those species that were present in fewer than three plots. In addition, we found that estimation errors in ITV decreased with increasing width of observed niche breadth. For consistency, we retained those ITV values whose species niche breadths were larger than 5% of the average niche breadth values for all species (for more details, please see Supporting Information Notes S1, Fig. S3).



**Figure 2.3** Scatterplot of individual species trait values ( $t_{ij}$ ) vs. plot mean trait values ( $\bar{p}_j$ ) for  $\log_{10}$ -transformed specific leaf area (SLA) ( $\text{mm}^2 \text{mg}^{-1}$ ) in our trait database. The black dashed line is the 1:1 line. Black triangles illustrate the observations of species  $i$ , in this case *Amomyrtus luma*. The blue line is the weighted least squares (WLS) regression line for this species and the slope of this line reflects its intraspecific trait variation ( $ITV = 0.89$ ). The red square shows its species mean trait value of  $\log_{10}$ -transformed SLA ( $\bar{t}_i$ ) at its position along the plot mean trait gradient expressed by  $\log_{10}$ -transformed SLA. The grey segment with arrowheads represents the niche breadth ( $R_i = 0.70$ ) of *Amomyrtus luma* along this trait gradient. See text for further explanation of these parameters.

### 2.2.3 SMA regression

We used standard major axis (SMA) regression (Warton *et al.*, 2012) to describe the best-fit lines of global pairwise intraspecific trait variation relationships and to compare those to global between species trait-trait relationships. To compare the pairwise intra- and interspecific trait variation not affected by sample size or species selection, we looked at exactly the same dataset for each pair of traits. Depending on the trait combination assessed, our tests were performed on data from between 8 to 470 species (out of 2064 species). We used the `sma()` function in the *smart* package (Warton *et al.*, 2012) in R software (version 3.6.2, R Core Team, 2019) to quantify the slopes with 95% confidence intervals and their associated coefficient of determination ( $R^2$ ) of the bivariate relationships for both trait ITVs (the slopes) and species mean trait values ( $\bar{t}_i$ ) (the interspecific variation) for all pairs of abovementioned eleven functional traits. We classified our eleven traits into three groups: LES-related traits (SLA, LDMC, LNC, LPC, LCC, Lth, Ltis, further referred to as LES traits), size and structure-related traits (LS, MH, SSD, see Díaz *et al.* 2016, further referred to as size-related traits) and root-related trait (SRL), and describe the results of the correlation of the traits within and between these three groups. In addition, we cluster some of the LES-related traits (SLA, LDMC, Lth and Ltis; together referred to as structural LES traits), given that these traits have a mathematical and possible physiological dependency (Pérez-Harguindeguy *et al.*, 2013) according to the following equation:

$$LDMC = \frac{1}{\text{leaf tissue density} \times \text{SLA} \times \text{leaf thickness}} \quad (\text{eq 2.4})$$

## 2.3 Results

Trait-trait relationships between species did not necessarily reflect trait-trait relationships within species. Most trait-trait relationships (39 out of 54) were significant between species (**Table 2.1**). 15 of these 39 trait-trait relationships between species remained significant within species, suggesting that they may represent plant strategies according to our framework (**Fig. 2.1a,b**). The other 24 trait-trait relationships between species are consistent with coincident coordination or coincident trade-off (**Fig. 2.1g,h**). Moreover, while some trait-trait relationships between species had an  $R^2 > 0.2$ , the strength of these relationships was reduced within species (Supporting Information Table S3). Finally, we did not find any evidence for alternative strategies (**Fig. 2.1f**) among the eleven traits under investigation (**Table 2.1**).

**Table 2.1 Different mechanisms based on pairwise trait-trait relationships within and between species.** Following our framework, the 54 pairwise trait-trait relationships between and within species were classified into different mechanisms (true trade-off/coordination, coincident trade-off/coordination, alternative strategy, or no plant strategy; see Fig 2.1). Each row represents a mechanism based on the significance of relationships within and between species. Columns represent different groups of traits: among LES traits, between LES and size-related traits, among size-related traits and between root-related and other traits. Each cell indicates trait-trait pairs from each trait group (column) that show a certain mechanism (row). Within each cell, the trait-trait relationships are listed in order of decreasing  $R^2$  of the between-species relationships. *Italicised trait pairs have an  $R^2 < 0.2$  for between-species relationships. The three within-species trait-trait significant ( $p < 0.05$ ) relationships are marked in bold ( $R^2$  range 0.183-0.202).*

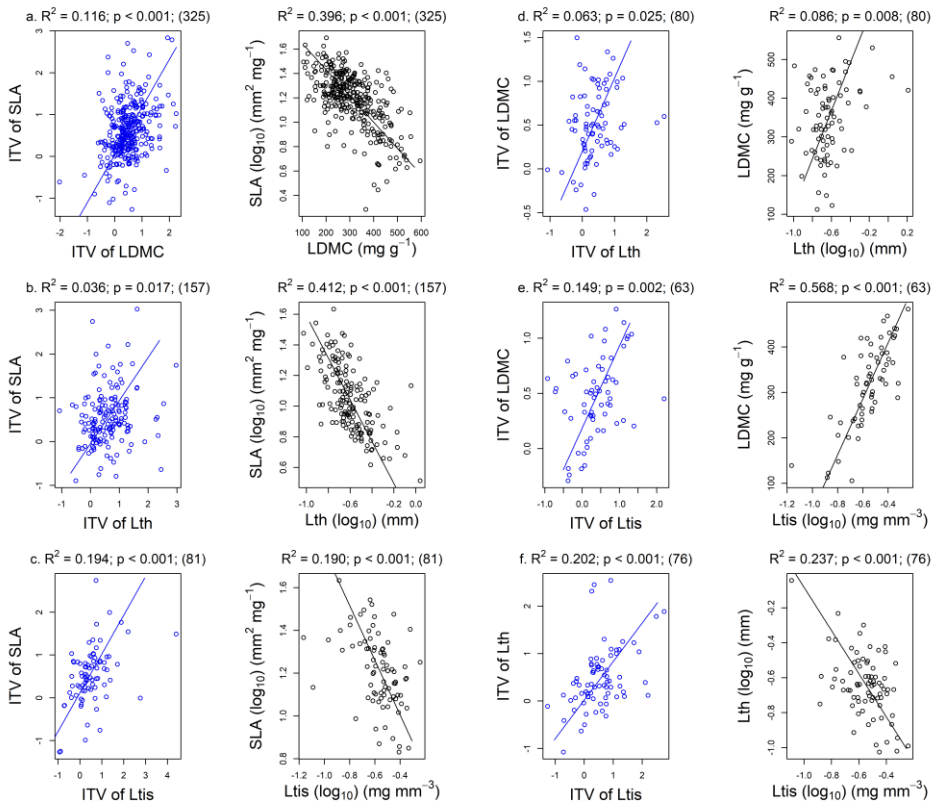
<b>Mechanism</b>	<b>among LES traits</b>	<b>size vs. LES traits</b>	<b>among size traits</b>	<b>SRL vs. other traits</b>
<b>True coordination</b>	LDMC-Ltis	<i>SSD-LDMC</i>		
	LDMC-LCC			
	LNC-LPC			
	LCC-Ltis			
	SLA-LPC			
	<b><i>LCC-Lth</i></b> <i>LDMC-Lth</i>			
<b>True trade-off</b>	SLA-Lth	<i>LS-LDMC</i>		
	LDMC-LPC			
	SLA-LDMC			
	LDMC-LNC			
	<b>Lth-Ltis</b> <b><i>SLA-Ltis</i></b>			
<b>Coincident coordination</b>	SLA-LNC	SSD-LCC MH-LCC LS-LCC <i>MH-LDMC</i> <i>LS-LNC</i>	MH-SSD MH-LS	<i>SRL-SLA</i>
	SLA-LCC	SSD-SLA		SRL-MH
	LNC-Lth	MH-LPC		SRL-Lth
	LPC-LCC	<i>MH-SLA</i>		SRL-SSD
	LPC-Ltis	<i>SSD-LPC</i>		
<b>No plant strategy</b>	LPC-Lth	<i>LS-Lth</i>		
	<i>LNC-LCC</i>	<i>SSD-LNC</i>		
	LNC-Ltis	LS-SLA LS-LPC LS-Ltis	SSD-LS	SRL-LNC SRL-LPC SRL-LDMC
		MH-Lth		SRL-LCC
		MH-Ltis		SRL-Ltis
		SSD-Lth MH-LNC		SRL-LS
<b>Alternative strategy</b>				

*Trait abbreviations: specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen content (LNC), leaf phosphorus content (LNC), leaf carbon content (LCC), leaf thickness (Lth),*

leaf tissue density (*Ltis*), leaf size (*LS*), maximum height (*MH*), stem specific density (*SSD*) and specific root length (*SRL*). Note, the trait pair *Ltis*-*SSD* was not assessed due to a lack of paired data.

### 2.3.1 LES traits

All structural LES traits (*SLA*, *LDMC*, *Lth*, *Ltis*) were positively related within species. Between species, *LDMC* was related positively with *Lth* and *Ltis* (**Fig. 2.4d,e**) while all others were correlated negatively (**Fig. 2.4a-c,f**). For some trait-trait relationships within species, the strength of the relationship was similar to that of between species (*LDMC* vs. *Lth*, *Lth* vs. *Ltis*, **Fig. 2.4d,e**).

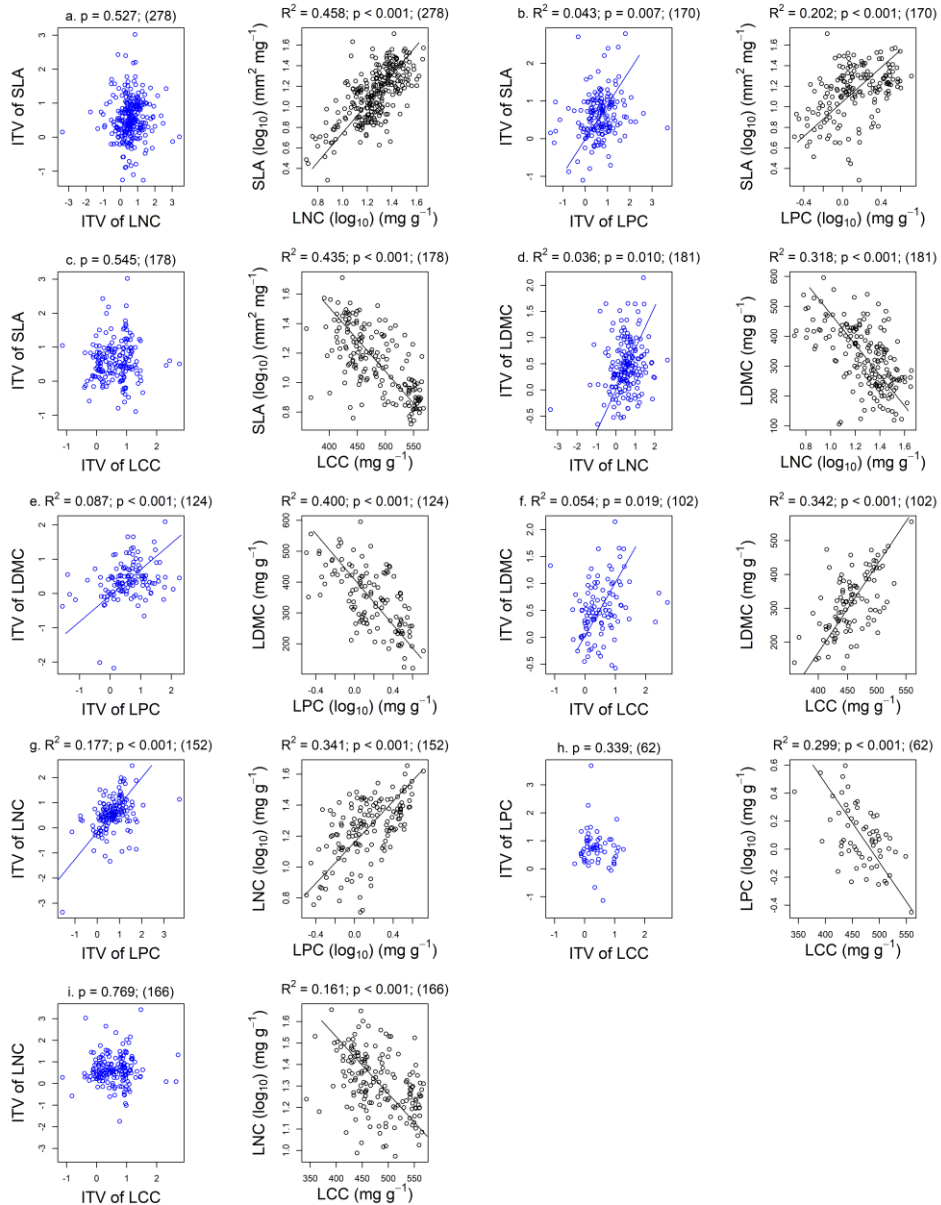


**Figure 2.4** Relationships among pairs of the structural LES traits, specific leaf area (*SLA*), leaf dry mass content (*LDMC*), leaf thickness (*Lth*) and leaf tissue density (*Ltis*), within species (showing intraspecific trait variation, in blue) and between species (showing interspecific trait variation in black) a. *SLA* vs. *LDMC*, b. *SLA* vs. *Lth*, c. *SLA* vs. *Ltis*, d. *LDMC* vs. *Lth*, e. *LDMC* vs. *Ltis*, f. *Lth* vs. *Ltis*. If a significant relationship was found, the regression line was drawn and the  $R^2$  was indicated above the figure, followed by the  $p$ -values. Numbers in brackets refer to the number of species included in the tests.



However, generally, within species trait-trait relationships were much weaker than that between species. At the extreme ends, we found SLA vs. L<sub>tis</sub> (**Fig. 2.4c**) with a similar strength of trait-trait relationships within and between species ( $R^2 = 0.194$  and  $0.190$ , respectively), while for SLA vs L<sub>th</sub> (**Fig. 2.4b**) the correlation within species was a magnitude weaker ( $R^2 = 0.036$ ) than between species ( $R^2 = 0.412$ ).

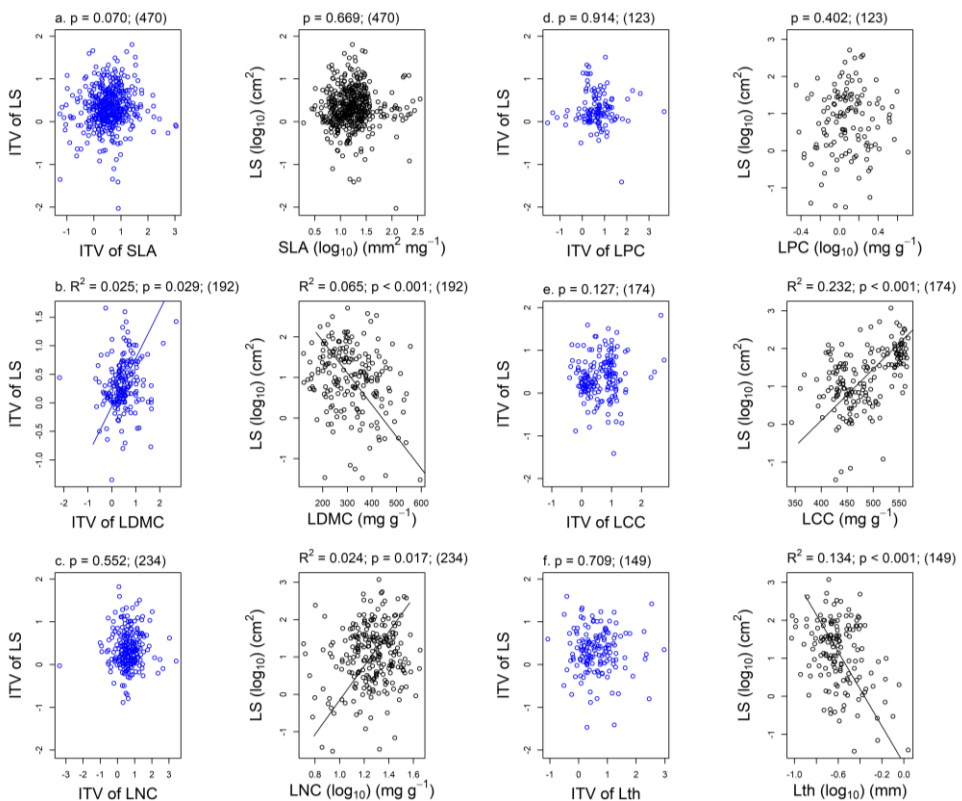
SLA and LDMC and other LES-related traits, LNC, LPC and LCC showed variable correlation within and between species (**Fig. 2.5**). SLA showed no within-species relationship with LNC, but a positive one relationship between species (**Fig. 2.5a**). LCC showed no relation within species and negative between-species relations with SLA, LPC and LNC (**Fig. 2.5c,h,i**), while LCC showed positive relations at both scales with LDMC (**Fig. 2.5f**). LDMC showed a positive within-species and a negative between-species relationship with both LNC and LPC (**Fig. 2.5d,e**). LPC was positively related both within species and between species to LNC and SLA (**Fig. 2.5b,g**). For all these traits, correlation within species was much weaker than that between species, as indicated by the  $R^2$ .



**Figure 2.5 Relationships among pairs of other LES-related traits, specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen content (LNC), leaf phosphorus content (LPC) and leaf carbon content (LCC), within species (showing intraspecific trait variation, in blue) and between species (showing interspecific trait variation in black) a. SLA vs. LNC, b. SLA vs. LPC, c. SLA vs. LCC, d. LDMC vs. LNC, e. LDMC vs. LPC, f. LDMC vs. LCC, g. LNC vs. LPC, h. LPC vs. LCC, i. LNC vs. LCC. If a significant relationship was found, the regression line was drawn and the  $R^2$  was indicated above the figure, followed by the  $p$ -values. Numbers in brackets refer to the number of species included in the tests.**

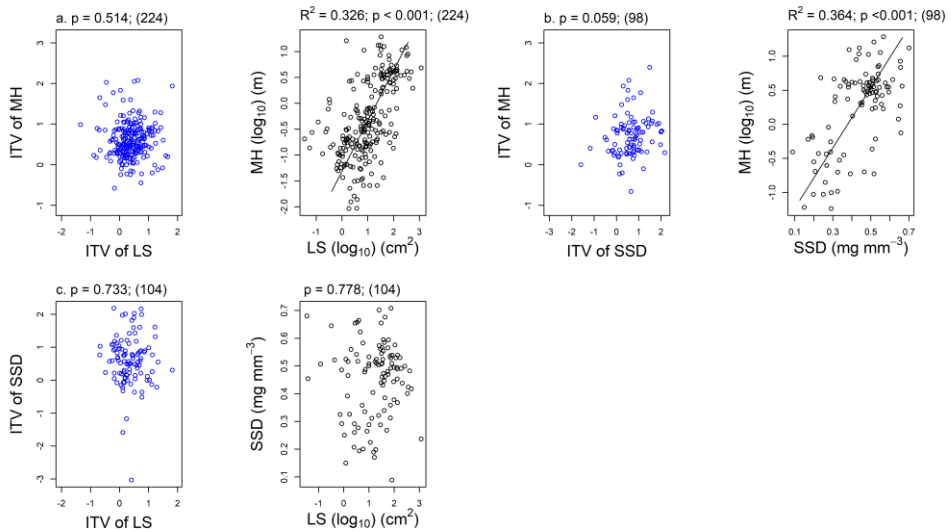
### 2.3.2 Size-related traits

Leaf size (LS) did not show within-species correlation with any LES traits (**Fig. 2.6a, c-f**), except for a very weak positive coordination with LDMC ( $R^2 = 0.025$ , **Fig. 2.6b**). Between species, LS was positively related to LNC and LCC (**Fig. 2.6c,e**), negatively to LDMC and Lth (**Fig. 2.6b,f**), and was not related to SLA and LPC (**Fig. 2.6a,d**). Other size-related traits, SSD and MH, showed similar patterns as LS (Supporting Information Table S3). None of the three size-related traits was related to leaf tissue density within or between species (**Table 2.1**, Supporting Information Table S3).



**Figure 2.6 Relationships of leaf size (LS) to some LES-related traits (specific leaf area (SLA), leaf dry matter content (LDMC), leaf nitrogen content (LNC), leaf phosphorus content (LPC) and leaf carbon content (LCC) and leaf thickness (Lth)) within species (showing intraspecific trait variation, in blue) and between species (showing interspecific trait variation in black) a. LS vs. SLA, b. LS vs. LDMC c. LS vs. LNC, d. LS vs. LPC, e. LS vs. LCC, f. LS vs. Lth. If a significant relationship was found, the regression line was drawn and the  $R^2$  indicated above the figure, followed by the  $p$ -values. Numbers in brackets refer to the number of species included in the tests.**

The three size-related traits (MH, LS and SSD) showed no relationship within species (**Fig. 2.7**), while MH had strong association with LS and SSD between species (**Fig. 2.7a,b**).



**Figure 2.7** Relationships among pairs of the size-related traits, MH (maximum height), LS (leaf size) and SSD (stem specific density), within species (showing intraspecific trait variation, in blue) and between species (showing species mean trait values in black) a. MH vs. LS, b. MH vs. SSD, c. SSD vs. LS. If a significant relationship was found, the regression line was drawn and the  $R^2$  indicated above the figure, followed by the  $p$ -values. Numbers in brackets refer to the number of species included in the tests.

### 2.3.3 Root-related traits

For root-related traits, we had sufficient pair-wise data only for specific root length (SRL). Between species, SRL was correlated with four (SLA, MH, Lth and SSD) of the other ten traits, but within species it was not related to any of these traits (**Table 2.1**, Supporting Information Table S3).

## 2.4 Discussion

Our study compared trait-trait relationships within and between species to assess whether the commonly reported interspecific trait relationships reflect plant strategies. Using a novel approach and a global dataset of 2064 species and eleven traits, we assessed whether the direction and strength of trait-trait coordination and trade-offs observed between species were still maintained within species. Our conceptual framework (**Fig. 2.1**) allowed us to discern between trait-trait

relationships that represent plant strategies and those that are generated by coincidental factors.

#### 2.4.1 Overall comparison patterns

Our conceptual framework (**Fig. 2.1**) identified trait pairs that represented true coordination or trade-offs that may represent plant strategies (first and second rows of **Table 2.1**). It also identified those trait pairs that expressed coincident coordination or trade-offs which might be mostly driven by common environmental drivers (third and fourth rows of **Table 2.1**).

As expected from our framework, true coordination or trade-off between species translated into positive within-species (ITV-ITV) relationships of corresponding traits. Moreover, those trait pairs that were not related between species, did not show any relationship within species either. We can therefore confirm that those trait pairs are not correlated at any scale (fifth row of **Table 2.1**). We did not find any evidence for our hypothesized occurrence of alternative strategies (sixth row of **Table 2.1**). This suggests that, if alternative strategies do occur, different species might not have the same strategy to deal with environmental pressure. This is in line with theoretical studies which suggested that alternative strategies can be expressed in multiple trait combinations (Marks & Lechowicz, 2006).

#### 2.4.2 Non-consistent patterns among different trait groups

Building on previously presented global analyses (Wright *et al.*, 2004; Díaz *et al.*, 2016), we expected that our approach would identify trait-trait relationships caused by plant strategies at least within the same trait group (LES and size-related trait groups). While it was true for LES traits, this was not the case in general. Within LES traits, there were many consistently significant trait-trait relationships at both between and within species scales. Consistently significant patterns were especially common for structural LES traits (**Fig. 2.4**), for which all significant trait-trait relationships between species were maintained within species. This pattern may be due to the mathematical and possibly physiological dependency among these traits (Pérez-Harguindeguy *et al.*, 2013, see section **2.2.3**).

For other LES-related traits, we noticed that both SLA and LDMC were closely associated to LNC, LPC and LCC between species (**Fig. 2.5a-f**), while within species LDMC was related more strongly (higher  $R^2$ ) to LNC, LPC and LCC than that was for SLA. This pattern may be related to the role of LDMC in protecting leaves against physical or herbivory damage. High LDMC species tend to have more

complex carbon compounds such as lignin in their leaves to protect them against herbivory (Pérez-Harguindeguy *et al.*, 2013), while low LDMC leaves are more palatable. Both LNC and LPC are considered to be important traits related to photosynthesis, and they were highly coordinated with each other both within and between species (**Fig. 2.5g**).

In contrast, relationships between the three size-related traits found between species disappeared when their within-species patterns were assessed (**Fig. 2.7**). This suggests that these traits may have different drivers, which may co-occur at large spatial scales, while being decoupled at the smaller spatial scales in which individual species prevail. For example, we found the apparent coordination of MH and SSD between species (**Fig. 2.7b**) was not because they were physiologically or eco-evolutionarily related (as these traits were not related within species). Instead, this between-species correlation was driven by a clustering of non-woody species at low MH and low SSD, while woody species clustered at a combination of high MH and high SSD (see Fig. S4 in Supporting Information), consistent with previous results (Díaz *et al.*, 2016, their Extended Data Fig. 3a & Fig. 4). The non-significant relationship between MH and SSD within species suggests that the variation of MH might be driven by light competition (Douma *et al.*, 2012) while the variation of SSD may be more related to cavitation protection than mechanical support (Hacke *et al.*, 2001; Sperry *et al.*, 2006).

Between size-related traits and LES traits, some statistically significant relationships between species occurred, which is to a large extent also consistent with the findings of Díaz *et al.* (2016), but these relationships were mostly absent within species (**Fig. 2.6a,c-f, Table 2.1**). These patterns of coincident coordination and trade-off may indicate different drivers for between-species *vs.* within-species trait relationships for those trait pairs. For example, Wright *et al.* (2017) showed that on a global scale, LS was dominantly affected by latitudinal and elevational gradients with different climatic conditions, while at local scales, LS was also influenced by various other drivers such as plant architecture, canopy display, plant hydraulics, soil fertility and herbivory. These findings may explain why LS was almost unrelated to any LES trait within species in this study.

While the trait-trait relationships within and between species were generally strongest within the LES traits, we included additional traits to show the general applicability of our approach. For example, we did not find relationships between SRL and any of the LES-related and size-related traits within species. While the low

sample sizes for SRL (compared to the easier to measure LES and size-related traits) may partly have caused the lack of trends, it may also be due to the ITV of SRL varying in species-specific ways along complex environmental gradients (Weemstra *et al.*, 2021). This analysis of traits not strictly associated with LES, like SRL, MH and SSD, helps to gain insight into the plant economics spectrum and the extents to and ways in which other traits are independent of the leaf economics spectrum.

### 2.4.3 Implications

Our study showed that many of the well-founded trait-trait relationships that occur between species became weaker (as shown by  $R^2$  values) within species or even disappeared altogether. In fact, except for the SSD-LDMC relationship (**Table 2.1**,  $R^2=0.095$ ), almost only trait-trait relationships internal to LES-related traits were maintained at the within-species level. Thus, a substantial number of trait-trait relationships previously coined as trade-offs or synergies appear to not indicate plant strategies in reality. Instead, it seems that various between-species trait-trait relationships are due to co-varying environmental drivers across large scales that may disappear within species. We expect coincident relationships with common environmental drivers to be apparent particularly along large environmental gradients across species (where effects of common drivers become larger than impacts of alternative plant strategies which would reduce the strength of the relationship). Within a species, such relationship would be easy to break because there are no fitness costs involved if the common drivers do not cause true coordination or trade-offs. Therefore, we would expect to see this trait-trait relationship between species but not within species.

There are some implications for future research based on our findings. We noted that trait-trait relationships within species were weak (the three strongest  $R^2 \sim 0.2$ , **Table 2.1**), which meant that within species, more than 80% of the variation of one trait was decoupled from the variation of other traits. Therefore, to improve our understanding on the role of intraspecific trait variation in plant strategies, it will be important to further investigate the drivers of ITV and its coupling among traits. Importantly, we did not observe any phylogenetic clustering in trait-trait relationships within species (see Fig. S5-9 in Supporting Information). Hence, we assume that physiological mechanisms and ecological constraints may play more important roles in driving plant strategies within species, than phylogenetic constraints, but this remains to be tested further.

Overall, distinguishing the mechanisms of trait correlation, as we did in this paper, is important for trait predictions, for example under the influence of climate change. If in a future climate, environmental drivers become decoupled, *e.g.* due to the rise of no-analogue climatic conditions, this may also lead to the breakdown of some trait-trait relationships between species. Using our findings, we speculate that such decoupling might particularly occur within the so-called size-related group of trait variation. Given that many of the traits investigated here are directly related to ecosystem processes, it stands to reason that the expression of some ecosystem processes are also affected. This will be important to account for in model projections.

Our novel conceptual framework (**Fig. 2.1**) can be used for further detailed study of extended species and trait sets. While our newly compiled database already included > 2000 species and eleven traits in tropical, temperate and boreal communities, much smaller datasets were available for any trait pair. A truly global concerted effort to compile a consistent and larger dataset of within and between species trait data will allow a similar approach to further elucidate the mechanisms of general plant strategies and incorporation in ecosystem modelling.

#### 2.4.4 Conclusions

Our study describes a novel approach to differentiate trait-trait relationships which may represent plant strategies from those due to common environmental drivers. By comparing trait-trait relationships between species *vs.* within species using a unique global database on intraspecific trait variation, we showed that almost only within the leaf economics spectrum, the between-species trait-trait relationships may represent plant strategies. Moreover, the frequent coincidental trait-trait relationships between species, caused by common drivers, imply that model projections on ecosystem functioning in a future climate should seriously consider decoupling of these trait-trait relationships. Our study emphasises the importance of describing the mechanisms behind trait-trait relationships, both between and within species, to deepen our understanding of general plant strategies.



## **Data Availability**

The data that supports the findings of this study is openly available in the Zenodo repository: <https://doi.org/10.5281/zenodo.5684291>. Code Availability: The R code used to build up the ITV database and generate the results of this study is openly available in the Zenodo repository: <https://doi.org/10.5281/zenodo.5680090>.

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## **Author Contribution**

P.M.v.B conceived the study; J.Z., E.C. and P.M.v.B developed the ideas; P.M.v.B and J.Z. collected the data; J.Z., E.C. and P.M.v.B conducted the analysis; J.Z. wrote the first draft. All authors contributed critically to the drafts and gave final approval for publication.

## **Supporting Information**

Additional supporting information may be found in the online version of this article: <https://nph.onlinelibrary.wiley.com/doi/full/10.1111/nph.17879>.