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MOUNTAIN GRASSLANDS
DYNAMICS: INTEGRATING
PHENOTYPIC PLASTICITY
IN A NEW AGENT-BASED
MODEL

ABSTRACT

Mountain grasslands provide numerous ecosystem services that need fine understanding and characterisation to be assessed and predicted. The vulnerability to climate change and the complexity of mechanisms driving alpine community dynamics require the development of new tools to predict the dynamics of these communities facing new conditions. Moreover, individual variation has large effects on community responses to external condition changes, as shown by multiple empirical studies but often overlooked in modelling approaches. In addition to these effects, intra-specific variability has contrasting potential impacts on coexistence mechanisms that need to be disentangled.

To answer both the need for a dynamic model of species rich communities and the integration of individual level , the model *MountGrass* was developed. It is designed around two main components: (1) a closed strategy space allowing a efficient representation of high species diversity, and (2) a plastic allocation mechanism integrating trade-offs between active and structural tissues, as well as between shoot and root tissues. In a first result part, after a parameter filtering step, the combined effects of allocation rules, species strategy and phenotypic plasticity on individual plants are studied. In a second part, the effect of plasticity is then studied at the scale of the community.

This work demonstrates the importance of phenotypic plasticity both at the individual scale and its role for community dynamics. While further work is needed to fully capture plasticity mechanisms, the model provides sound starting point to further explore the role of intra-specific variability in coexistence mechanisms, the resistance and resilience to drought events, or the detection of regime shift in this type of systems.

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I

INTRODUCTION

1 CONTEXT

1.1 Global change: how to describe the future of alpine ecosystems

1.1.1 The value of ecosystems

1.1.2 Global change

1.1.3 The need for mechanistic models

1.2 Community dynamics: complexity emerging from parts and the role of phenotypic plasticity

1.2.1 The limit of classic patterns

1.2.2 The rise of individual-based approaches

1.2.3 When phenotypic plasticity makes things complicated

2 AIMS, OBJECTIVES AND OVERVIEW

2.1 Aims: understanding and prediction

Functioning Diversity of : drivers, mechanisms, species and strategies
Flexibility:
structure: genericity, experiments, plasticity

2.2 Objectives: a new agent-based model for plant community dynamics

2.2.1 Generic framework for multi-species and plastic plant modelling

2.2.2 Effect of phenotypic plasticity on plant growth and community dynamics

2.3 Thesis overview

INDIVIDUAL LEVEL
COMMUNITY LEVEL

Why the how: what makes these objectives valid

The machine

The results

II

BACKGROUND: COMMUNITY DYNAMICS, TRAITS AND PHENOTYPIC PLASTICITY

1 UNDERSTANDING COMMUNITY DYNAMICS: DRIVERS AND THEORIES OF COEXISTENCE

1.1 The question of coexistence

If ones want to better understand and predict dynamics of complex systems, they first need to understand how such complex is assembled. If it is easy to observe diverse ecosystems (from bacteria, to plants, insects or algea), it is challenging to determine the processes that 1) group the entities together (in time and space), 2) maintain an apparent stability in the group composition (at least at a certain spatial and temporal scale). This set of processes are called the assembly rules. Different type of processes are at stake to maintain a community and the general filters are illustrated in the figure ??.

We can imagine biotic filtering as an physical filter, the same way abiotic filter is often illustrated, but this image does not translate the dynamic and complex nature of underlying processes. Biotic filtering emerge as the result of all the interactions between the entities that make it through the other filters. And how these interactions, direct or indirect, play together to see the stability of the diversity.

Plankton paradox in homogeneous system, where abiotic and dispersion should have little role into maintenance of species diversity.

Focus on interaction: chesson modern coexistence theory.

Chesson vs Tilman. Chesson focuses on interaction and 2 by species, give central idea of stabilizing vs fitness difference.

Tilman focuses more on resources, how the use and impact on resources affect competition and can enable coexistence, but limited coexistence according to this criterion: plankton paradox. No heterogeneity, no temporal dynamics

Other things being equal hypothesis (in models at least) does not allow the full diversity to emerge.

One mechanisms alone seems to not be enough to explain fantastic diversity explain in natural ecosystems. However there are multiple theoretical mechanisms that support species diversity and that should taken into account in community models: diversity of resources, spatial and temporal variability, frequency dependent effects, etc...

1.2 Abiotic and biotic factors: from potential to realised niche

Abiotic drivers main thning at global scale... Then interactions and competition.

The concept of ecological niche serves as a great tool for theoretical research on coexistence. It encompass in a convenient way both abiotic and biotic drivers of one species distribution. The Hutchinsonian niche also captures the multidimensionality of persistence and reproduction.

1.3 The complexity of community dynamics

Succession coexistence and forest models. Dynamics of resources, influx versus impact. Storage effects. Heterogeneity. But how does it link to traits.

From the multiple first attends to explain coexistence with one particular mechanism, scientific community realised that indeed multiple mechanisms are at work to make species diversity in ecological community. + multiple drivers that filter down. + temporal effect (metacommunity, invasion, equilibrium vs long transitions) This multiplicity highlight the need for unifying framework able to cover this diversity of mechanisms and dimensions.

2 CONSIDERING STRATEGIES AND FUNCTIONAL TRAITS

2.1 The continuity of functional ecology

The paradigm shift toward functional ecology allowed the shift from discrete to continuous representation of species. This change make easier the representation and study of plant communities, especially along conditions or management gradient. Despite the advantages of functional traits, close comparisons and links with theoretical approaches should be used carefully, and underlying assumptions should be interrogated.

2.2 How trade-offs make strategy space

Diversity of mech: diversisty of strategies. more or less independent.

The multiplicity of mechanisms in these systems lead to similar diversity in plant strategies. These strategies are captured in a strategy space drawn by independent trade-offs. Such trade-offs can be captured and embodied thanks to functional traits.

2.3 Modelling diverse plant community

The use of strategy spaces in models allow the representation of high diversity in a common plant functioning framework requiring limited number of parameters. Such approaches are very useful to follow the dynamics of communities in a mechanistic framework.

3 THE IMPORTANCE OF INTRA-SPECIFIC VARIABILITY

3.1 Intra-specific variability change the rules

More interest in trait distribution, variability and diversity. → Get to look at intra-specific variability. RISING INTEREST...

Jung: not always in the same way [Jun+14]
[Kic+13] [Sie+15] [Alb+12] [Vio+12]

[HSL16] [CVK10] [TL16] [Ros+15] [Val+15] [barabas_effect_2016] [Jun+10]

...AND CONTRASTING EFFECTS

The intra-specific variability has been observed to be both an important part of community functional diversity, but also a way the community respond to changes in conditions. In addition to the empirical evidence of this importance, theoretical approaches support contrasting effects of such variations on coexistence mechanisms, evolutionary processes and community responses to climate event or invasion. It is crucial to disentangle different sources of intra-specific variability in order to understand potential effect on ecosystem dynamics.

3.2 Phenotypic plasticity: a specific case of intra-specific variability

phenotypic plasticity is the capacity of a species to produce individuals with the same genotype but different phenotypes. This difference in phenotype should be an active process, not the results of direct alteration of the phenotype by external factors without changes in internal functioning. This change in internal functioning process has the objective ² to match the phenotype with expected future conditions to maximise the individual fitness. The expression "expected future conditions" is key here, as it is this projection that drives the plasticity.

² in the sense it has been selected because it provides this capacity

Active plasticity is used for predominantly anticipatory, and often highly integrated, phenotypic changes in response to some environmental cue or signal, and reflect modifications of developmental pathways and regulatory genes. Forsman - 2014

Passive plasticity, on the other hand, may stem from direct environmental influences on chemical, physiological and developmental processes, and is generally not considered anticipatory, but a mere consequence of the environment,

such as stunted growth owing to low resource levels.

Phenotypic plasticity requires two main components: (1) a projection of future conditions, (2) a link function between conditions and phenotype. The link function can have an additional parameter in the form of the current state of the individual, parameter that alters the form of the function.

3.3 Beyond the mean and the bell-shape: towards more mechanisms in representing intra-specific variability

The same way the neutral theory is simplifying and brings little understanding to underlying processes and relies on strong hypothesis, considering intra-specificity as a purely random mechanism is insufficient.

WHY

Bell shape do not appear in altitude gradient...

Strong theoretical hypothesis

Asymmetric and symmetric competition

If most of changes are plasticity or selection: it changes the effects on interactions and niche.

CONSEQUENCES

What are the possible effects? probably it does not affect interaction like [HSL16] supposes (even if they talk about variations, their conclusions may not be extendable to plastic variations). May change a lot the balance between abiotic filtering and biotic filtering.

As ecology shifted from species to traits syndromes, it seems that it needs to go from syndromes to distributions and drivers. The complexity of living communities requires to go further down and consider the individual scale. This is made possible by the accumulation of more and more numerous and detailed data, the improvement of statistical and simulation tools.

3.4 Toward an integrative framework of plant strategy and phenotypic plasticity

Bradshaw? Dewitt

New simulations tools for understanding community dynamics should try to both include multiple coexistence mechanisms and plant strategies, and focus on individual level mechanisms of competition, growth and survival. This can only be achieved in a constraint high dimensional strategy space based on physical and biological trade-offs. Individual level modelling allows the integration of multiple sources of intra-specific variability: genetic diversity and phenotypic plasticity. Phenotypic plasticity being driven by the perception of environment, it cannot be simply described by normal random distribution and should receive more attention. This focus is particularly important considering both the lack of understanding of this phenomena and the consequences for plant communities.

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III

MODELLING ALPINE GRASSLANDS WITH MOUNTGRASS A GENERIC FRAMEWORK INTEGRATING PHENOTYPIC PLASTICITY

The objective of this chapter is to develop the core concepts of the model, introduced in the previous chapter, and explain the structure and design choices made during the model development. The first part focuses on the general context of alpine grasslands and some coexistence mechanisms at stake. The following part details the definition of the strategy space and the modelling of phenotypic plasticity while introducing the key concepts of species memory and individual experience. Finally, the last part is a detailed description of the model following Grimm recommendations [Gri+06].

1 ALPINE ENVIRONMENT: CONDITIONS, RESOURCES, AND PERTURBATIONS

1.1 The scales of alpine grasslands

The scale is a determinant variable in the quantification of mechanisms that structure ecological communities [Bel+13], and therefore in modelling approaches. It is chosen based on structures that the modeller intends to explore and determine the upper limit of mechanisms the model can reproduce. Large scales will favour geo-climatic and dispersal effects [KMoo] while small scales will focus on direct plant interactions processes or resource heterogeneity [Sou+12; Mai+13a; Tau14]. This is true for spatial scale, but also temporal scales. Because mechanisms studies at large scales like dispersion, invasion, speciation occur over long time scales whereas mechanisms occurring at smaller spatial scale, like competition, facilitation, disturbances play a role on shorter time scales, spatial and temporal scales are often correlated. The scales are also dependent on the studied environment. There is a high contrast between highly productive environments like tropical forests and unproductive environments like mountain grasslands. The dimensions of individuals themselves are a constraint on the scales: while tropical trees grow few tens of meter high and above one meter diameter [], alpine grasses do not exceed half a meter [korner_alpine_2011]. Similar differences of the order of magnitude can be observed for life cycles between long live tree and annuals or bi-annuals grasses. The focus of this work being on plant functioning and interaction mechanisms, the scale of the model will be around the meter, while the temporal scale will be in the order of the season.

The same way the scales are constraint by the size or length of the individual, the resolution should be close to the size of the modelled entities. The resolution is also determined by the focus of the model: interactions between individuals must be distinct and not blended to hope see the emergence of spatial patterns. Cell size and time step length should be small enough to take into account heterogeneity that is an important driver of diversity. For these reasons, the spatial resolution is set up to the centimetre and the temporal resolution to the day (can be changed but processes might not scale well).

THE SCALE

THE RESOLUTION

Once the resolution is fixed there is always the temptation to increase the size, or scale, of the system. This should be avoided for two main reasons. (1) the increase of scale with relatively fine resolution lead to a high increase in computational power required for simulations that are already complex. (2) there is a high chance that the processes modelled at fine resolution lose their sense when scale increases. Indeed, as mentioned, the importance of processes at stake is often dependant on the scale the system is studied. The effect of higher scale processes are often taken into account in inputs or parameters[1]. Calibration these parameters against certain data is a way to better understand these processes [lagarigues].

COMPLEXITY AND PERFORMANCE

1.2 Resources: light and water

As mentioned in the previous chapter, resource fluctuations, heterogeneity, and competition are important factors for coexistence. Unlike animals, plants mainly compete for the same resources: light, water and nutrients. Light is the source of energy that allows the transformation of inorganic carbon into organic matter through photosynthesis. Water has multiple functions in plants: transport, structural support, and oxygen supply for photosynthesis. Nutrients are used in the construction of cells and cell walls, and especially the production of proteins that act as cell machinery.

1.3 Perturbations: frost, grazing, and mowing

The most notable specificity of mountain grasslands is the climate. While there is a wide range of mountain grasslands type, the focus of this document is in French Alps. The alpine climate in France is characterised by cold winter with snow precipitations and dry summer. The growing season is relatively short and spread between May and October in low altitude, and June and September in high altitude **need some charts here**. The particularity of this habitat is the presence of snow cover during winter that protects soil, rhizomes, and seeds from negative temperatures. Because of this, seasons are decomposed in the model based on the snow melt in spring/summer and the first snowfall in winter. While a rise in temperature is needed to allow snow to melt down, frost event can occur after the beginning of the season. Such events represent strong environmental filter for non-adaptive plants that do not invest in specific resistance mechanisms to favour early germination and growth. Therefore there is a strategic trade-off between germination date and early growth with frost resistance.

CLIMATE

Another specificity of alpine grasslands is that they are subject to changing management practices. Mountain grazing by domestic cattle was fairly common in the Alps, but changes in agricultural practices and a decrease in productivity due to drought lead to less and less grazing or mowing for fodder in alpine grasslands. These two types of management have different impacts on the community. While mowing is non-specific and favours small plants, herbivory is known to be specific when the production is greater than the grazing pressure. Leaves with high nutrient content and low structural tissues content are generally favoured because of high input and high digestibility. The grazing pressure

MANAGEMENT

plays as ... mechanisms as it favours conservative species with lower competitive ability.

OTHER FORM OF HERBIVORY

2 MULTI-DIMENSIONAL STRATEGY SPACE, CARBON POOLS, AND TRADE-OFFS

2.1 Multi-dimensional strategy space and allocation pools

2.1.1 The strategy space in *MountGrass*

In an ecological agent-based simulation model a species will be defined by its values for the species-specific parameters. They can be estimated from experimental data [Tau14; Mai09; Loh+14] or be picked from a strategy axis [Rei+06; KMoo] composing a strategy space [Wes98]. The diversity of the species pool will depend on the number of values for each of these specific parameters, or traits, and the number of these traits. Each trait increasing the dimension of the strategy space [Lau14]. The ambition of this model being to simulated rich plant communities, the definition of these axes is crucial. Trade-offs between traits are excellent applicants for these specific parameters as they reduce the dimensionality of phenotypes to a small number of dimensions [Wri+04; Díaz+16; Rei14] while keeping the information of traits needed to describe the plant functioning. Trade-offs emerge from ecological and physical or biological constraints, by considering these constraints Darwinian demons are avoided.

WHAT IS A STRATEGY SPACE

While considering too many axes does not improve community description, a certain number is needed to have strategic diversity [Lau14]. This is intuitively explained by the fact that each trade-off is closely related to a particular aspect of fitness or mechanism for coexistence (*e.g.* reproduction, competitive ability, resistance to resource shortage, predation, etc.). In this model, multiple aspects of plant life are represented: germination with the germination rate for storage effect [Cheeo; Adl+06], dispersion with seed mass [Wes98] or tissue construction cost [RWE92; Wri+04; Rei14]. Main components of plant growth and life history are covered by such trade-offs and driven by mechanisms shared by all vegetation systems. Because of that, the model has a great potential of genericity and diversity. It can be easily adapted to other plant communities with specific calibration, and extended to couples of biological process and differentiation axis (*e.g.* root herbivory and associated resistance carbon pool). The the trade-offs used in the model are detailed in the model description below ². These axes should, in such models, be independent, (*i.e.* it is physically and biologically possible for a plant to take any position in the space drawn by two given axis) and result from physical or biological laws (ensuring that impossible strategies are indeed excluded from the model). First, it is a condition for parsimony of the

² see section 4.

model. The second and more interesting reason is that any trade-off emerging from the model should have an ecological interpretation [Mai+13b].

One way of constraining plant strategies to certain axes is to consider allocation trade-offs [KMoo; Rei+06]. An allocation trade-off is the translation of the mass conservation rule that prevents the allocation of biomass to distinct carbon pools. If biological functions are related to organic matter pools (photosynthesis to leaves, water and nutrient uptake to roots), then the sum of biomass to invest in each carbon pool (therefore in each function) cannot exceed the total available biomass: leaving the plant with a choice on the balance between the different functions. Allocation trade-offs have the advantage to be easily implemented and be intuitive. By design, a partitioning factor value corresponds to a position on the related strategic axis. In *MountGrass*, five main trade-offs are captured by allocation trade-off: (1) development vs reproduction: partitioning factor between reproduction and maintenance of vegetative tissues (when plant is mature), (2) persistence vs dispersion: partitioning of reproduction biomass between persistence (storage) and production of new propagules (seed/clone production), (3) aboveground vs belowground competition: investment between shoot and root, [KMoo; Rei+06; Tau14], (4) slow vs fast: construction cost trade-offs between active and structural tissues in both shoot and root and (5) growth vs resistance: partitioning between stored biomass and frost resistance carbohydrates [Cai+04]. This last trade-off can be extended to other carbon pools of specific resistances, for example to herbivory. Modification of these coefficients during life history is a way to introduce plasticity in the model. The rules driving such changes for some of this partitioning parameters are described in the following section.

One of these trade-offs, (4), is key and related the construction cost of organs (independently leaves and roots). Highlighted at the global scale and for leaves, the Leaf Economic Spectrum [Wri+04] draws a strategic differentiation axis from conservative slow species and exploitative fast species. The construction cost has long been identified as a factor of strategic differentiation in plant communities [Wes98]. This strategic axis, being related to many functional traits: SLA, LDMC, LNC, leaf longevity, Amass, etc. [Wri+04] is of crucial importance. First, these traits are closely related to the characterisation of plant communities and the assessment of services [Gri98]. Second strong links and correlations can be made between these soft traits physiological traits [wright_worldwide_2004; Cra+02; Rei+03]. Finally, a species resource use strategy is closely related to its responses and vulnerability to changing conditions [Poo+09; DHM14; Del+15]. The traits related to this trade-off play a major role both in individual growth and physiology and in community services and response to a gradient. Therefore it is essential to the model. Questioning the underlying mechanisms for such strong trade-off is necessary to implement satisfying representation in the model.

Change this: maybe start with Shipley results, then composite stuff. Question: should it be here, or in the following part ?

These trade-offs between highly productive tissues with low construction cost and short lifespan called exploitative, and more conservative strategy with

longer lifespan but lower productivity are mainly observed thanks to soft traits such as SLA for LNC [Wri+04]. Mechanistic models require traits related to physiology and organ performance [Sou+12; Loh+14], but a link can generally be done between these traits and soft traits. However, traits such as SRL or SLA are composite traits emerging from different organ properties [Rys96; Joh+17], where tissue density and organ thickness are the main determinants. "A necessary trade-off between allocation to structural tissues versus liquid phase processes" has been identified by Shipley et al. [Shi+06] as one of the two main factors for the leaf economic spectrum to emerge. Such allocation trade-off can indeed explain differences in construction cost as the liquid phase corresponding to the "active" part of plant tissue, the cell content, have much lower dry volumetric mass than its "structural" counterpart, the cell-wall. Also, active tissues containing the protein machinery for photosynthesis and water absorption, a higher proportion of high protein concentration tissue would be correlated to higher nitrogen concentration in the organ on the "fast-slow" spectrum, along with a higher mass-based photosynthetic rate [Rei14]. On the other end, the structural tissues give the organ a higher lifespan [MEH01; Rys96] that compensate for lower productivity [WWRoo]. Such trade-off can be apply to both shoot and roots [Cra+02; Tjo+05; Rei14]. From that, the decomposition of organs between active and structural tissues constitutes a strong basis to model construction cost trade-offs as the main parts of the global strategy space.

The Similar axis of differentiation has been demonstrated for roots [[tjoelker_linking_2015](#); Rei14]. The necessity for independent similar axis for leaves and root can be discussed with respect to coordination between shoot and root activities. Because perfect equilibrium cannot be guaranteed in all conditions, strict coordination cannot be taken as a principle for the reduction of strategy space. Moreover, empirical results suggest small deviations from coordination are common [FKW15]. The leaf economic spectrum being conserved at the intra-specific level [Hu+15] is another reason to include such trade-off as it would be a good basis for phenotypic plasticity [Fre+13].

The use of allocation trade-offs allows the construction of a generic multi-dimensional strategy space where a high diversity of species can potentially coexist. Because this space is based on physic laws, it ensures the non-existence of Darwinian demons and does not limit the species or individual plants to tested parameters and strategies. To be complete the link between carbon pool allocation and physiology must be determined within the respect of similar biological or physical laws.

2.2 Craft a trade-off: active and structural tissues

Allocation trade-offs offer great flexibility and are easily understood and implemented. However, when they control the value of traits (SLA or SRL) involved in multiple processes, a balance must be found to avoid that: (1) one process is ignored because has a low relative importance onto fitness (becoming useless to the model), (2) the effects of processes involved show strong response curves to the allocation and there is only one global¹ optimum. The idea behind a trade-off is that multiple positions are viable in different conditions or in association

¹ I use the term global here to designate the multidimensional space draw by the axis of interest and other variables play a role in involved process (e.g. resource availability, temperature etc...).

with other strategies. The leaf-economic spectrum, in addition to relying on the active-structural tissue trade-off, also requires "*an evolutionary trade-off between leaf photosynthetic rates, construction costs, and leaf longevity*". This trade-off is explored in this section of the document.

In the framework of the model, plants share the same global parameters, and the maximum photosynthetic rate should be the same. Because photosynthesis relies on the exchange of gases (CO_2 , O_2 and H_2O) and the interception of light, it is related to exchange area. Considering one shared parameter for maximum area-based potential exchange rate satisfy both the need for a shared parameter and a way for plants to vary their mass based exchange rate by changing its proportion of active tissues. This is in agreement with the LES that a strong relationship between mass-based traits and limited ones for area-based variables [Wri+04], and explain the first part of the trade-off between photosynthetic rate and construction cost. The second part is the relationship with the longevity. The longevity is often correlated to SLA in empirical studies, however, this is mainly explained by differences in tissue density and toughness than in thickness (another component of SLA) []. For this reason, we can directly link the leaf longevity to active tissue proportion. Respiration is also increased by the increase of the proportion of photosynthetic tissues [kleidon; reich]. We have now a trade-off between a gain function (exchange area gain by changes in densities) and a cost function (tissue turn over and respiration). This should be enough to explain different strategies [westoby]. However, the model needs internal limits to avoid the gain function to lead to only active tissue organ (or only structural). These limits are required to allow individuals or species to change position along these axes (plasticity or strategic shift). The convex shape of gain function in association with a minimal cost (minimum turn-over cost above maximum potential gain) is enough to limit the allocation to structural tissues only. To avoid allocation to only active tissue, that would correspond to an organ made of protoplasts, the cost function needs higher than the potential gain. To achieve that an exponential function is chosen. This choice ensures that the potential gain function has an optimum different from the borders. (see figure).

Active got closer to optimum, but less active and positive gain in more conditions. Can I demonstrate this with formulas ? (gain = function(condition))

GAIN AS FUNCTION OF CONDITIONS

The potential gain is not only a function of active tissue proportion but also depends on resource availability. Changes in resource level imply changes in the slope of gain function and a shift of the organ optimum for tissue allocation. This shift makes more conservative strategies more interesting when resources are scarce, while more exploitative allocation strategies are better for high resource availability. This link between optimum allocation and resource level could be used to define the best phenotype according to experience conditions, but the organ strategy cannot be disconnected from the whole plant strategy and allocation.

The phenotype (within the subspace of vegetative allocation) depends both on the individual efficiency of organs and the balance between shoot and root

activity. This balance often used to model plant plastic allocation and considered between light and nitrogen [lohier; soussana]. In the context of mountain grasslands and global change, the water... The integration of nitrogen as a limiting solution is discussed in a later chapter. The balance between shoot and root activity being key in overall performance, the root:shoot ratio (RSR) will be determined as a function of estimated availability.

2.2.1 Species memory and phenotype determination

phenotype = ensemble of response trait values. Emerge from default trait + environment.

Composite traits are defined by the interaction of different, independent, driving traits. What is a driving trait? Biology: genetic information. This genetic information is selected by climatic conditions. If we can make a link between optimum value for a trait and environmental conditions, then store external conditions and use link between.

MEMORY OF SPECIES: A DRIVING TRAIT

The decomposition of organs organic matter in active and structural carbon pools makes a link between allocation and physiology and draws a subspace within the strategy space where individuals can move and change their phenotype. Limiting mechanisms restrain the viable options to realistic values along these axes. Within this space, the resource availability and external conditions play a major role in the expression of the strategy.

VEGETATIVE PHENOTYPE AXIS

Flexible, allocation based, diversity and movement

3 MODELLING PHENOTYPIC PLASTICITY

3.1 Plasticity as a strategy: between species memory and individual experience

3.1.1 Concept of active plasticity as a strategy

The active plastic response is highly integrated and involve a lot of regulatory processes. It is impossible to represent all regulatory processes involved in an APR (because of our lack of knowledge and their complexity). Alternatively, the concept of *integrated response* can be conceptualised. It supposes link, or coordination, between the experienced conditions and the phenotypic response. This can be translated, in the model framework, by the existence of an explicit link between a representation of external conditions and a phenotype matching this conditions: the ². Another key work is *anticipatory*. It supposes that the plant knows, or at least have an idea of the future conditions. This is really the point of an active plastic response: change the phenotype to better match future

DECOMPOSITION OF PLASTIC RESPONSE

² the use of the word *allocation* is justified here since the phenotypic plasticity in *MountGrass* is reduced to changes in allocation.

conditions. A representation of future is also called a . The projection and the allocation rule together form the active plastic response.

If allocation rule is not obvious and is discussed latter(see paragraph 3.2), the idea of projection is fairly intuitive. The projection will correspond to a value for a given metric that represents the external conditions. It can be resource availability level, temperature, herbivory risk, etc... If such metrics can be given at the community scale, it makes sense to use a plant-centered measure of these variables for two reasons: (1) take into account the spatial heterogeneity, (2) plant experience of conditions is necessarily egocentric. The details on how experienced conditions are interpreted by plants in *MountGrass* are described in section 4.

Active plasticity is now represented by a projection and allocation rule. However, how a species can control the whole process is unclear. In theory, both projection and allocation rule can species specific. In nature plants generally have structurally similar regulatory processes¹ and response to external stimuli is translated (and stored temporarily) thanks to the accumulation of chemical compounds[need-references]. These mechanisms suggest that, while the allocation rules are mainly shared, individuals vary on the information level (i.e. the concentration of phytohormones), or in the context of the model: plant vary in projection. This control of active plasticity is supported by the model design. The number of rules that can drive the allocation is reduced and discrete, while the projection is multi-dimensional (one dimension per external variable considered), continuous and highly flexible with a reduced number of parameters². For this reason is chosen to be the of active plasticity, while the allocation rule is and between all species. Therefore an individual with fixed projection won't be actively plastic, despite the fact that it could express apparent plasticity because of external factors: reduced resource availability, grazing, frost damage, etc... The model has now a concept for active plastic response³ controlled by the projection of external condition. The next question that needs to be answered is: how do species differ in their plastic response ?

CONTROL OF PLASTICITY

¹ see box ??.

² details in paragraph *estimation of conditions* in section 4.

³ In the rest of the document terms *plasticity* or *phenotypic plasticity* will refer to *active plastic response*.

In *MountGrass* , the projection of external conditions is the mean for plants to alter their phenotype in response to changes in experienced conditions. Since the allocation (or driving) rule is shared by all plants, if the projection of external conditions is also shared by all plants, then is the response still active plasticity? The first intuitive answer is *yes*, since the conceptual framework is respected and plants would react to changes in conditions that would affect the projection. But, such response would be equivalent to a direct external control of the climate on the phenotype. In such case, species would not have control on how the phenotype varies, that would be fully controlled by shared projection and shared allocation rule. This is passive plasticity. To have proper active plasticity, the species need to be able to the plastic response. If species can regulate plastic response thanks to species-specific parameters, plasticity becomes a . This is in agreement with Bradshaw vision of phenotypic plasticity as a trait, or a character, subject to selection and evolutionary processes[Bra65; Bra06]. How do species regulate plastic response to make it a strategy?

SPECIES SPECIFIC PLASTICITY

Plasticity: expected environment -> phenotype, here phenotype is equivalent

to biomass partitioning, that means expected environment -> allocation coefficients. Then memory -> expectations -> allocation. Because low dimensions, and we want diversity, and the link between memory and allocation might not be a function (one memory give exactly one optimum allocation), in the model this relationship is not verified. Species-specific traits are used to allow for different strategies to be associated with the same memory (different plants won't have the same strat, despite sharing the projection)

3.1.2 Projection of external conditions: between species memory and individual experience

The projection is the way plant controls phenotypic plasticity. A projection is an idea of the future based on available information and on the understanding of a phenomenon. Ones could discuss what is the understanding of the climate by plants, while others can focus on how to represent such understanding and state that fine molecular regulatory processes can reproduce and store such information. The focus is on the construction of the projection with respect to the different sources of information a plant has: (1) its experience of climate and external factors, and (2) its ancestors' memory¹.

[BUILD A PROJECTION](#)

¹ see paragraph 2.2.1.

While, for any given individual plant, the experience of external conditions varies in time, the memory stays fixed. There is a clear contrast between the variable experience of conditions and the fixed species memory. A way to represent different strategies and the level of control the plant apply on projection is to vary, between species, the relative weight of species memory against individual perception. This species-specific parameter, the , sets the of the projection with respect to individual experience. The capacity to adapt the phenotype to changing conditions is directly linked to the projection changes. High confidence in species memory translates in low amplitude of projection variations, and though in low active plasticity.

The calculation of projected resource availability levels, or temperatures, are detailed in the dedicated paragraph of the model description. The key message is that the species has control on plasticity with both its confidence in species memory and the said memory that alters the projection. The relative impact of memory and confidence is described in figure ??.

3.2 Driving rules of allocation

Allocation rules are determinant in the model behaviour as it is shared by all species, and link the projection of conditions with the phenotype. Multiple options are possible to drive plasticity, but they can be divided into two main categories: (1) determining, (2) directive. Functions from the first category fully determine the phenotype (within the plastic strategy space), while functions from the latter group direct the phenotype toward a sub-space and other parameters are needed to determine the exact new phenotype.

The two type of rules have different strengths and weaknesses that are detailed in table ??

One of the assumption made by the conception of plasticity developed in this document is the existence of a tight relationship between experienced condition

Strength or weakness	Determining	Directive
Phenotype fully determined	●	○
Risk of convergence	●	○
Reduction of functional diversity	●	○
Discrepancy between parameters	●	○
Strong plasticity effect	●	○

Table 3.1: Two types of allocation rules: strengths and weaknesses

and fitness, and a subsidiary assumption in the implementation of this plasticity is that this function can be captured, or modelled, by the same functions that drive plant growth. In other words, simulating individual growth, using the estimated/projected conditions as parameters, day by day, is enough to capture the link between environmental conditions (experienced by the focal plant) and plant growth¹.

... How these rules fit into that ?

The driving rule of plasticity defines whether or not the choice of the phenotype is fully determined by the projection of external conditions or also constrained by some species-specific parameters. The effect of this balance between projection and parameters has a large influence on the model behaviour. In any case, the projection is the main control on individual plastic response to change in conditions, offering possibilities to modulate individual plasticity despite an allocation rule shared by all species. The role of both projection and allocation rule will of particular interest during the analysis of the impact of phenotypic plasticity of plant growth and community dynamics.

While the representation of plasticity as a strategy increases both model potential species diversity and potential diversity of response [REoo; Kic+13], plasticity itself may reduce diversity. Indeed, plasticity lead to changes in phenotype in response to condition changes, while these phenotypic changes are unlikely to be identical for all individuals, their general convergence points will probably be similar. Plasticity is a mechanism that is likely to contract the space of expressed values for plastic traits. Therefore, it is hard to analysed the effect of plasticity on functional diversity without disentangling the direct effect on the expressed trait values, and the indirect effect by changes in performance and interactions. Nonetheless, some external mechanisms² can prevent convergence of phenotype: (1) changes in competitive hierarchy may lead to differences in individual experience of conditions, (2) specificity of the external driver, e.g. selective herbivory of more digest species, (3) relative position of the optimum phenotype. Asides from these external mechanisms, there are internal controls of active plastic response: the projection and the plastic allocation mechanisms. It is easy to imagine numerous projections and allocation mechanisms, however, they are susceptible of emerging only if they have a positive impact on fitness overall. Considering the diversity of plastic response is a research question in itself, and I will not try to answer it in this document. Nevertheless, the progress in the understanding of the effect of plasticity on performance and potential diversity this work provide will certainly help further work in that direction. In this context, the use of species-specific control over the projection of conditions is already a step forward and prevent total convergence³. Indeed, without considering multiple allocation algorithm within a same community, having the plasticity

¹ that takes here the value of fitness proxy

THE PARADOX OF PLASTICITY

² impact the drivers of plastic response, not the response itself

³ in addition to directive allocation mechanisms, see below subsection 3.2

as a strategy [Brao6] (controlled by a species-specific trait, as opposed to many existing individual-based-models) allows interesting questions to be addressed. The questions of cost of plasticity is central in the understanding of this mechanisms [DSW98; AAR09], and could lead to mechanisms of co-selection between resource use or reproductive strategies with plasticity strategies. A first step in this direction consists in looking at how plasticity can have different impacts on performance of species with different strategies (conservative versus exploitative).

3.2.1 On the difficulty to match strategy and conditions.

As mentioned, the framework of plasticity developed in this document relies on a strong link between condition estimation and the phenotype, that is supported by the assumption that similar link exist between condition experienced by the focal plant and its fitness. If this assumption is correct, then the initial phenotype (or default phenotype) should match the optimum phenotype defined by this link expressed by the allocation rules and the species-specific memory of conditions. One main difficult emerges here: because the processes involved in plant growth are numerous and complex, it is not possible to determine analytically what phenotype is the best (considering the memory of conditions). This point is discussed in the following paragraph as the understanding of the component of plant performance is a first step to understand the model's behaviour and plasticity mechanisms. Ones could compute the convergence phenotype for a given memory of external conditions for each possible memory combinations, and map the phenotype to the memory. This solution is a good alternative to analytical solution when the later is not possible, but it comes with the disadvantage of very high computational cost that is prohibitive for calibration procedures. When a model is only directive,

WHY MATCH PHENOTYPE TO MEMORY

Here lies a difficulty, indeed, the design of the model favours modularity and different allocation algorithms do not share the same constraints. 2 things here:
- why having default traits even if they do not match the optimum defined by the allocation rule.
- the difficulty to determine an optimum phenotype with analytics.

Complexity between organ, overall efficiency, and equilibrium. Try to formalise each function and show the link between these elements.

EFFICIENCY AND PERFORMANCE

The multi-dimensionality of fitness.

IS PERFORMANCE FITNESS?

Fitness and competition: where niche theory and coexistence theory coexist
[letten_linking_2017]

The projection of external conditions, driving the plastic allocation of organic matter, lies on a balance between species memory and individual experience. Its design makes of plasticity an axis of strategic differentiation alongside the other strategy axis. Thanks to this innovative design, the model can be used to examine the ecological relevance of plasticity in different conditions and in association with different strategies. The effect of allocation rules and projection stability can be explored independently or conjointly for

a better understanding of relative importance of allocation and plasticity.

4 ODD DESCRIPTION OF THE MODEL *MountGrass*

This document is a detailed description of the *MountGrass* model. This description is based on the ODD protocol of Grimm et al. The model is inspired by multiple other forest and grassland models (for grassland models see particularly Taubert [Tau14] and Lohier [Loh+14]). It differentiates itself from these models by the incorporation of phenotypic plasticity in a generalizing framework for plant functioning. This allows it to be used to both to explore the fundamental effects of phenotypic plasticity the dynamics of rich grass communities and the impact of the phenotypic plasticity on plant interactions. The general approach and the practical details are further detailed in this document.

4.1 Model overview

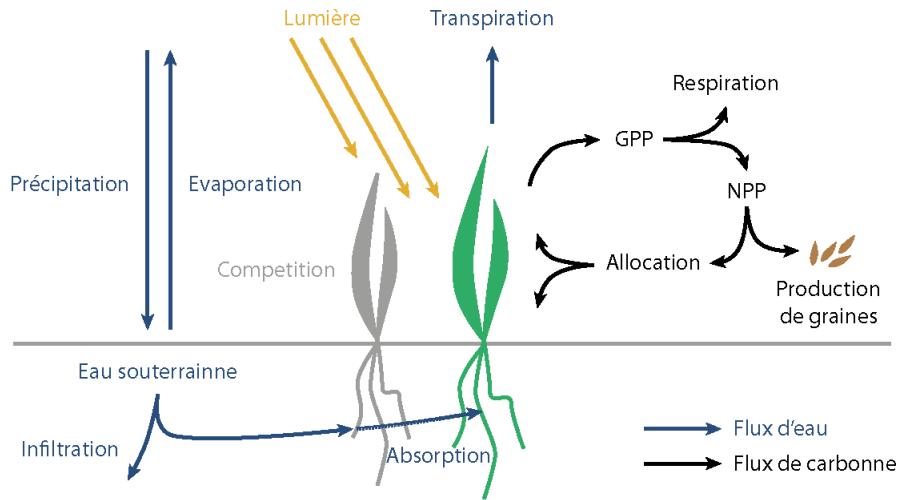
4.1.1 Model purpose

The development of *MountGrass* is motivated by the need for a flexible tool to explore the complex dynamics of mountain grassland communities, in the context of global change. This tool should, by a better understanding of community dynamics and representation of plant strategies and interaction, also help in the assessment of ecosystem services in new conditions. We believe that to capture the dynamic of such communities, we need to understand and represent first the individual response of plants to fluctuating levels of resources, and the impact of plants on the resources. Individual responses and relative impact should follow general rules of plant physiology but also integrates specific behaviour based on the species resource use strategy and individual characteristics. Therefore the model should allow following distinct individuals from different groups (e.g. species) in a spatially explicit environment where they compete for resources.

Moreover, since we focus on the community levels, coexistence mechanisms are important and we should include a certain number of these if we want to maintain diversity to observed levels. These mechanisms include: multiple resources competition (water and light), spatial and temporal heterogeneity of resource levels, strategic trade-off between species, perturbation mechanisms (frost, management), link to meta-population, etc...

The model is built to try to satisfy conditions to reproduce and explore mountain grassland community dynamics. In the current version of the model (*MountGrass2.0*), a generalist approach has been privileged, and focus on some coexistence maintenance mechanisms and integration of phenotypic plasticity framework. In this state, the model has to be seen as a toy model with good generalisation potential. The link between to ecosystem services are not included, but we can easily imagine to compute them from the community trait distribution. All processes and mechanism are detailed below.

Figure 4.1: Model overview



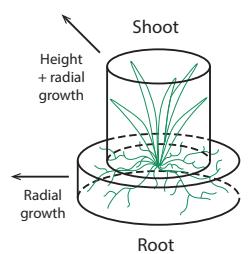
4.1.2 State variables

In mountain grasslands individuals (tillers) generally do not grow big and interact only with close neighbours and form little patches. And thus it is possible to represent a rich community at a fairly small scale (\approx dm or m), but the spatial resolution should be relatively fine (\approx cm) to capture inter-individual interactions. Because the model is intended to explore climate change impact on mountain grasslands, it can run on multiple growth seasons separated by snow-covered periods, but must also integrate the intra-seasonal variations at daily scale. Mountain weather (mostly temperature) is known for its large hourly variations, it would, however, require too much computational power to consider such variations. In addition to this argument, we believe that even though they imply physiological flexibility and specific strategies for plants experiencing these conditions, they will not have a huge impact on overall community dynamics changes caused by the climate change. That why hourly variations will not be considered and physiological processes are estimated at the daily timescale.

SCALES

The plants are described in the model by state variables described in table 4.1. The best way to understand how plant are represented is to imagine two homogeneous cylinders on top of each other, the shoot cylinder varying in radius and height representing the light acquisition (and shading) zone, and the root cylinder varying only in diameter (because of shallow soil in mountain ecosystems) representing the water acquisition zone. These cylinders are centred on cells of the torus simulation plan.

PLANTS



In addition to classic variables (age, position, height, diameter, shoot and root biomasses) the plants are described by traits, that can be species-specific or non-specific, others are variable (SLA, SRL) and depend on particular traits that are unique to this model: the **ratio between active tissue and structural tissue** (in shoot and root) (variables $\frac{act}{str} ag$ and $\frac{act}{str} bg$ in table 4.1). This couple of traits come from the evidence that numerous trade-off observed in leaves can be explained (at least partially) by this allocation trade-off between active tissue

Figure 4.2: Plant geometry and growth axis.

producing organic matter, but increasing respiration, and structural tissue that increase tissue lifespan.

Variable	Description	Unit
x	x position on the grid	cells
y	y position on the grid	cells
age	age	days
sp	species	-
BM_{ag}	above-ground biomass	g
BM_{agsen}	senescent above-ground biomass	g
SLA_{sen}	senescent above-ground biomass	$cm^2.g^{-1}$
BM_{bg}	below-ground biomass	g
stem	stem biomass	g
$\frac{act}{str} ag$	above-ground active on structural biomass ratio	g/g
$\frac{act}{str} bg$	below-ground active on structural biomass ratio	g/g
h	height	cm
r	shoot radius	cm
r_r	root radius	cm
$light_{exp}$	above-ground potential resource availability	$gH_2O.\text{leaf area}$
$water_{exp}$	below-ground potential resource availability	$gH_2O.\text{root area}$

Table 4.1: State variables of individual plants
SPECIES

Plants are characterised by state variables that describe them individually, but they also share common characteristics with individuals of the same group, (we will refer as *species* to talk about this group in the rest of the document even though it could be a group at another scale (i.e. population, clones). These species are the groups present in the meta-population and that can invade the simulated ecosystem. There are described by multiple traits characterising the strategy of the species (table 4.2).

Trait	Range (close range)	unit	trade-off or strategy
seed mass	(0.00001 - 0.001)	g	seed output vs seedling productivity
maturity	-	green biomass	flowering time vs reproduction potential
fract_dev	0-1 (0.05-0.6)	-	blooming vs persistence
fract_rep	0-1 (0-1)	-	reproduction vs persistence
geometric constant (k_g)	(0.1 - 20)	-	competition sensitivity vs self-shading
plasticity stability	0-1 (0.8-1)	-	genetic information vs experience
initial water resource	(0.001 - 0.05)	$gH_2O.cm^{-2}$	water resource niche
initial light resource	(0.001 - 0.05)	$gH_2O.cm^{-2}$	light (in H_2 equivalent) resource niche
$\frac{act}{str} ag,d$	(0.03 - 0.3)	$g\cdot g^{-1}$	active vs structural tissue
$\frac{act}{str} gg,d$	(0.03 - 0.3)	$g\cdot g^{-1}$	active vs structural tissue
mean temp.	(0 - 5)	°C	early vs late germination
germination rate	0-1 (0.5 - 1)	-	good season bet-hedging
thickness	(0.012 - 0.05)	cm	WUE vs light efficiency (not in this version)

Table 4.2: Species traits

The seed-bank is the transition state between the different seasons. Individuals may persist thanks to stored resources, but they can also reproduce by the

SEED-BANK

production of new individuals. A lot of grasses use clonal reproduction, in addition, or replacement of sexual reproduction. This type of reproduction is characterised by a persistent link between the newly produced individuals and the parent one that allows the two to communicate and exchange resources. Such dynamics are complex and costly to represent as the link between ramets must be stored and strategies defined for the resource distribution (see Oborny 2012) for more details on clonal growth modelling). To avoid too much complexity, it is possible to approximate the representation of clones to big seeds with little dispersion around the parent plant¹. For this reason, reproduction mechanism is reduced to sexual reproduction mechanism with the production of "seeds". Seeds are stored in the seed-bank and only defined by their species and positions.

The soil is an important aspect of the model as it drives (with the precipitations) the water competition between individuals. It is however limited, as in numerous vegetation models, to a grid characterised by its capacity to retain water, and its depth. Only the first component (water retention capacity) is spatially variable and is described by the critical water content (minimum soil water content), the saturation water content (maximum water content, the water non absorbed leaves the system we assume the same root depth for all species), and the current water content (temporally variable, depending on competition, precipitation and evaporation, between the critical and the saturation water content) only dynamic variable among the three.

4.1.3 Process overview and scheduling

As mentioned the model runs at a daily step to capture individual responses to conditions and over multiple seasons to capture long temporal dynamics. Some processes occur (or are evaluated) at the daily time-step, some at the season time-step. The following ordered list presents the different processes and the scheduling over days and season of one simulation.

One season can be divided into the following parts:

- *germination*: marks the beginning of the season when the ground is no more snow-covered;
- *growing season*: consists in daily processes like competition, production of organic matter (OM), allocation, and death lottery;
- *reproduction-invasion-persistence*: marks the end of the season when the first persistent snow-fall occurs. OM invested in reproductive tissues turns into seeds that are sampled to create the seed-bank. Seeds from the meta-population may integrate the seed-bank. Persistent perennial loose most of their biomass but storage (and eventually stem) and regrow from stored organic mass at the beginning of the following season.

The *growing season* part consists in all processes evaluated every day of the growing season. These processes are:

- *light competition*: the individual potential photosynthetic activity is computed based on average daily light and shoot properties;

¹ This would take advantage of dispersion kernels. Not implemented in the current version. Dispersion is uniformly random within the simulation plan

SOIL

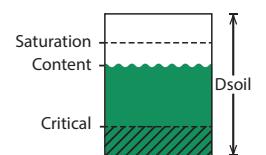


Figure 4.3: Soil section.



Figure 4.4: Seasons cycle in MountGrass .

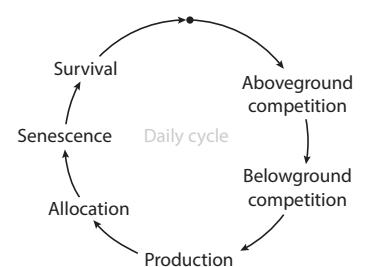


Figure 4.5: Processes in order during the daily cycle.

- *water competition*: evaporation and the individual water update (and potential water uptake) are computed based on potential transpiration, water availability and potential evaporation;
- *production*: respiration and production are computed to give the net productivity in OM;
- *senescence*: based on lifespan a part of tissue is no longer active.
- *death*: death of individuals based on their age and their desiccation stage (number of consecutive days with negative growth).
- *allocation*: allocation of produced OM to the different carbon pools of the plant.
- *grazing/cutting*: (optional) grazing or cutting of plants to a certain height. The grazing can be selective.¹

¹ remarks in grey are features or components implemented in the model but not used and-or calibrated.

4.2 Design concepts

4.2.1 Design concepts

This part clarifies the rules that drive the dynamics of the model.

The purpose of the model is to understand the rules that drive the community responses. We tried making the community dynamics emerge from the underlying processes of plant growth, resource use, and reproduction. That means that population dynamics are at least partially emergent from the surviving and reproducing individuals. *Partially* emergent because it depends on the invasion rules applied to the system. The traits and biomass distribution that describe the community are completely emergent from the individual traits exposed by the individuals and their relative biomass and abundance.

Plants have in theory many options to adjust their phenotype and increase their fitness in response to changes in environmental conditions (resource availability, temperature, ...). High diversity of mountain grasslands suggests that multiple strategies coexist and that individuals do not change to converge toward a unique strategy. These strategies are set up at the species level by the species-specific traits (see table 4.2). Therefore, individuals may only adapt morphological traits but not strategic traits (unless there is an epigenetic mechanism added). These morphological traits are the relative biomass of shoot and root, the relative proportion of active and structural tissues in each leaf, and roots (controlling respectively the SLA and SRL and the overall resource acquisition cost)². Geometry traits (distribution of leaves and roots within space) are not considered plastic as grasses have far less control over their geometry than forbs or trees. Root distribution plasticity has been shown to greatly improve the individual and community productivity (Gemini article), but to keep the model (and implementation) simple we will ignore root distribution plasticity and foraging strategies to focus on allocation problems instead of spatial distribution questions. Shallow soils and relative small rooting zone are also arguments to ignore spatial distribution plasticity for roots.

In the model, the realised fitness can be estimated as the capacity of plants to maintain themselves or their descendants through time. It emerges from the productivity, allocation to storage or reproductive carbon pools, and survival.

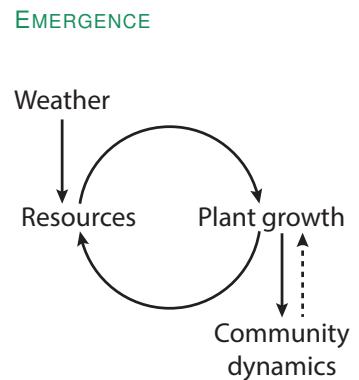
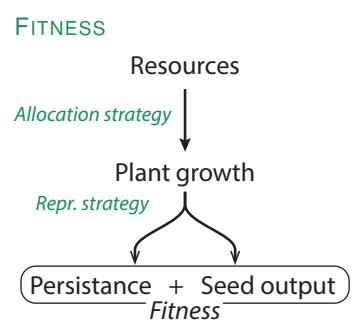


Figure 4.6: Population dynamics emerging from plant growth and weather.

ADAPTATION

² and optionally the proportion of stored OM dedicated to frost resistance and not to growth



Assessing fitness as the average number of persistent individuals is, however, a bit hazardous in simulations limited in time and to a relatively small spatial scale. Plus, plants cannot easily make a prediction of such variable to adjust their phenotype. They need a proxy function for fitness that integrates measures of external conditions to evaluate the best strategy to develop. As said above, this strategy should be a composite between the species strategy and individual adjustment specific to the individual experience of the environment. Plant fitness is estimated by individual plant thanks to a gain function integrating current phenotype, species strategy, and projection of future conditions. This gain function can take multiple forms and be more or less constraint. In the context of the model, the function should include a measure of productivity that relies on the principle of functional equilibrium - that is the allocation of organic matter to maintain the balance between the shoot activity (transpiration) and root activity (water uptake). This equilibrium can be achieved by changes in shoot:root ratio only, or also changes in active over structural tissues ratio. Further details about the gain function are discussed in the dedicated paragraphs (4.3.3). A more complex form of functional equilibrium incorporating nutrients (like nitrogen) could be added to the framework of this model.

Adaptation or plasticity mechanisms imply that agents have an insight of what will be the future. In *MountGrass* we consider that plants have two main sources of information. The first source of information is the genetic information. Indeed, the evolutionary process of genotype selection has led to the selection of genotypes adapted to the local conditions. This selection relationship can be seen as a link between environmental conditions and genetic information. Because plants cannot fully predict future environmental conditions, they grow following (at least partially) the plan contained in genetic information that match conditions where previous generations grew in. This is an internal *a priori* information about the external conditions. If the conditions where the seed grows change from the conditions its genotype has been selected for, the genetic information does not fit the environmental conditions is not sufficient enough to build a working phenotype. In this case, if the plant has a plasticity capacity, it can integrate the second source of information, in the form of the experienced conditions, to its "a priori" and forge a new estimation of what conditions will be. One question emerges to this idea is: how to create an image of future conditions and how to balance the genetic *a priori* information with the experienced information? This balance can be described by a term of "reactivity" that describes the relative weight of genetic and experienced information. A reactive species will give a higher weight to experienced condition information, whereas a stable species will give a higher weight to genetic information.

PREDICTION

The way the two source of information are brought together and used to define the plant phenotype is at the core of plant strategy and is the main feature of the model *MountGrass*.

4.3 Details

Further details on daily mechanisms are described in the following paragraphs.

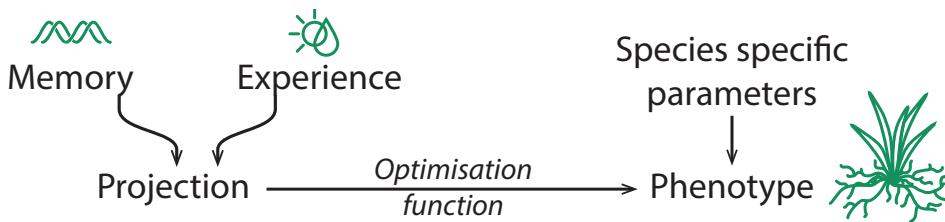


Figure 4.8: Genetic and perceived information are both considered to determine the phenotype.

Figure 4.9: Overview of the model inputs and outputs.

4.3.1 Initialisation

The model doesn't need particular initialisation if the state of the community species pool, the seedbank, and the soil are given as inputs. Otherwise, a set of $E(n/s)$ individuals are created from a set of s species (randomly generated if not given) and randomly positioned on the soil grid, where s and n are respectively the number of species and the approximate number of individuals within the grid. Soil grid is also randomly generated within default ranges for critical and saturation water contents then slightly smooth, and homogeneously filled ($filling = \frac{w_{cont} - w_{crit}}{w_{sat} - w_{crit}}$).

4.3.2 Inputs

MountGrass needs system state information (individuals, species, seed-bank and soil) and climate data. If the state of the system is not completely given, then the complete state is generated in the initialisation. The daily climate data at must contain the following fields:

- *date*;
- *radiance*, in Watt.m^2 ;
- *precipitation*, in mm;
- *mean temperature*, in K;
- *mean day temperature*, in K;
- *min temperature*, in K;
- *max temperature*, in K;
- *relative humidity* in %;

Vapour pressure deficit is then computed from temperature and relative humidity.

The climate data must explicitly differentiate the seasons (delimited by the first day of the year without snow and by the first day of the second semester with snow).

4.3.3 Submodels

Individuals from the seed-bank randomly germinate according to their species-specific germination rate. Germination consist of investing a percentage (*mob* parameter) of the seed mass into shoot and root biomass according to default

GERMINATION

traits. This is coupled with a round of random seed death following uniform law of parameter $seed_{surv}$. Living non germinating seeds stay in the seed-bank until the next season.

Daily processes

Light competition is central to all vegetation model as it constrains the photosynthetic activity and so plant growth. To avoid costly calculation of ray propagation we assume vertical homogeneous top radiation. Relief and orientation effects are taken into account in the computation of irradiance data.

Light competition sub-model allows calculation of individual potential photosynthesis activity and light at soil surface for evaporation calculation.

Competition for light is calculated independently for each pixel, potential photosynthetic activity is then aggregated at the individual level. Each pixel can be seen as a column of homogeneous layers containing at least one individual (top layer). For each layer, the light transmission is computed based on leaf density.

$$I(h) = I_0 e^{-LAI(h)} \quad (4.1)$$

where $LAI(h)$ is the cumulative LAI at the bottom of layer l (between h and $h + \Delta_h$) defined as the homogeneous layer delimited by the top of consecutive individuals in the same pixel. The LAI is calculated like this:

$$LAI(h) = LAI(h + \Delta_h) + \Delta_h \cdot pix_width^2 \sum_{i \text{ in } l} d_i \cdot coverage_{i,p} \quad (4.2)$$

where d_i is the individual leaf area density corrected by the coverage ($0 < coverage < 1$) of the pixel p by the plant i , $\Delta_h = (h_l - h_{l-1})$ is the height of the layer l .

Following Thornley and Johnson, the potential photosynthetic leaf activity is calculated as:

$$P_{leaf}(h) = \frac{\alpha \cdot I_{leaf}(h) \cdot P_{max}}{\alpha I_{leaf}(h) + P_{max}} \quad (4.3)$$

where $I_{leaf}(h)$ is the light absorbed by the leaf at height h , α the initial slope of the light response curve and P_{max} the maximum photosynthetic rate per unit of area and unit of time. I_{leaf} is the radiance at the leaf surface, derived by correcting the radiance at the top of the layer following the equation used in Taubert with the extinction and transmission coefficients k and m :

$$I_{leaf}(h) = \frac{k}{1-m} I(h) \quad (4.4)$$

The equation (4.3) can be integrated over the leaf surface by mixing it with equations (4.1) and (4.2) to give the total potential photosynthesis for layer l in pixel p :

$$P_{leaf}(p, l) = d_i \cdot coverage_{i,p} \cdot \Delta_h(l) \int_{h_{bottom}}^{h_{top}} P_{leaf}(h) \quad (4.5)$$

the total leaf potential photosynthesis is then calculated as follow:

$$PS_{pot} = \sum_{p \text{ in shoot}} \sum_{l \text{ in pixel}} P_{leaf}(p, l) \quad (4.6)$$

Potential photosynthesis must then be converted to potential transpiration to define the water demand. The conversion from photosynthesis to transpiration

LIGHT COMPETITION

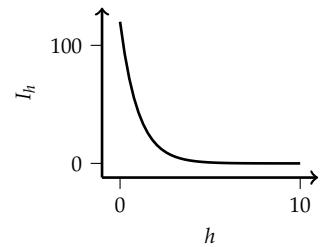


Figure 4.10: Net gain function and its first derivative.

Looks like there is some kind of mismatch here.

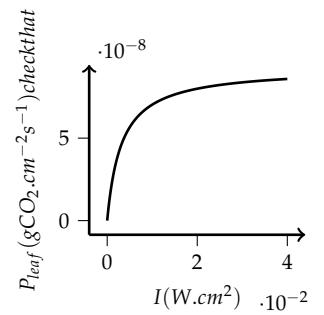


Figure 4.11: Photosynthetic saturation function

is done by dividing the potential photosynthesis by the water use efficiency (*WUE*). The potential activity of leaves are also dependent on the regulation of stomata so the transpiration can be written:

$$transp = \frac{PS_{pot} \cdot g_{red}}{WUE} \quad (4.7)$$

Photosynthesis depends on gazes exchanges at the leaf surface. These fluxes result from relative concentration in carbon dioxide and water, and from the stomatal conductance. Stomatal conductance is reduced and limits productivity when vapour pressure deficit is too high ¹. A linear relationship describe this relationship:

$$g_{red} = 1 + VPD_{g_red} \quad (4.8)$$

STOMATAL REGULATION

¹ *g_{red}* is set to 1 for current version to avoid potential problems between allocation and regulation

Potential evaporation is calculated for each pixel depending on the light at soil surface:

$$\beta = 0.25 * (1 - \cos(\frac{\theta}{\theta_{sat}} * \pi))^2 \quad if water_{cont} \leq water_{sat} \quad (4.9)$$

$$\beta = 1 \quad otherwise \quad (4.10)$$

$$PET = 0.0023 \cdot \sqrt{(T_{max} - T_{min})} * (T_{mean} + 17.8) \quad (4.11)$$

$$evap = PET \cdot \beta \cdot I_{surface} \cdot daylength \quad (4.12)$$

Water competition is also computed at the pixel level. To determine the water uptake, first the individual water demand is computed as the minimum between the transpiration and the potential water uptake. Transpiration demand per pixel is easily calculated by dividing the total potential transpiration by the volume in the pixel $V_{i,p}$ over the overall root volume V_i . Water potential uptake is the product of root area in the pixel and root water uptake rate reduced by the water availability reduction factor U_{lim} , leading to the water demand for individual i in pixel p :

$$transp_i(p) = transp \cdot \frac{V_{i,p}}{V_i} \quad (4.13)$$

$$Wpot_i(p) = Root_{area}(p) \cdot U_{max} \cdot U_{lim} \quad (4.14)$$

$$Wdem_i(p) = min(transp_i(p), Wpot_i(p)) \quad (4.15)$$

$$(4.16)$$

EVAPORATION

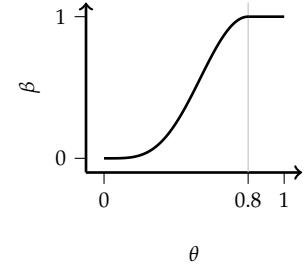


Figure 4.12: Evaporation limitation function.

WATER COMPETITION

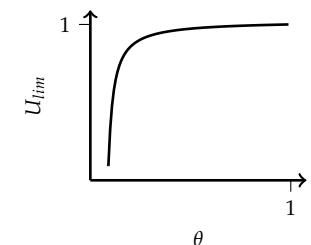


Figure 4.13: Water uptake limitation response function to soil saturation

$$U_{lim} = exp \left(\beta_\theta \left(\frac{1}{\theta_s - \theta_{crit}} - \frac{1}{\theta - \theta_{crit}} \right) \right) \quad if \theta < \theta_{crit} \quad (4.17)$$

$$= 0 \quad otherwise \quad (4.18)$$

The total water demand per pixel is then the sum of all individual water demand of the pixel and potential evaporation. If the total water demand exceeds the total water availability (W_{av} product of water content and soil volume in the

pixel) then the available water is distributed proportionally to the individual demand.

$$W_{up_i} = W_{dem_i} \cdot \frac{W_{dem_{total}}}{\min(W_{dem_{total}}, W_{av})} \quad (4.19)$$

The potential water uptake (W_{up}), non limited by the transpiration is calculated the same way but considering $W_{dem_i} = W_{pot_i}$ in equation (4.19).

Because the water competition is computed at the pixel level, there is no compensation between two pixels containing respectively not enough and too much water.

No radial flow of water between pixel is implemented in the model. This simplification leads inevitably to edge effects, but allows simpler implementation and is partially covered by the effect of the pixel size. Indeed, increasing pixel size would have similar effect in the pixels at the border of the rooting zone than radial flow because it would increase the potential water pool plant has access to.

Once potential and realised transpiration and water uptake are computed, plant productivity can be calculated.

Following previous vegetation models, the respiration is decomposed in growth respiration and maintenance respiration. The first is function of trait values, biomass and temperature:

$$R_m = \left(R_{act} \cdot (Act_{ag} + Act_{bg}) \right) \cdot daylength \cdot T_{effect} \quad (4.20)$$

where R_{act} is the respiration rate of active tissues, and Act_{ag} and Act_{bg} are the active biomass pools in shoot and root.

Net Primary production (in CO_2 equivalent) can then be calculated the difference of GPP and respiration, then converted in OM production thanks to tissue carbon content (under the assumption of fixed carbon content for leaf and roots between species):

$$NPP_{carbon} = (1 - R_g) \cdot (WUE \cdot \min(w_{up}, trans_p) - R_m) - BM_{total} * Pl_{cost} \quad (4.21)$$

$$NPP_{OM} = NPP_{carbon} \cdot (12/44) / TCC \quad (4.22)$$

Here R_g is a fixed parameter but is set to 0 if the difference between gross productivity ($GPP = WUE \cdot \min(w_{up}, trans_p) - R_m$) and maintenance respiration is negative. Pl_{cost} is the plasticity cost as calculated in the dedicated paragraph below.

Temperature has a effect of plant activity, this effect can be modelled by a bell shape function around an optimum value of 20 °C. See Lohier for details.

PRODUCTION, AND RESPIRATION

TEMPERATURE EFFECT

The projection of environmental conditions is central in any implementation of phenotype plasticity. Differences between the current perception of environment and the projections lead to adjustment of phenotype to increase fitness. In the model *MountGrass* this projection results from the averaging of two key concept: memory and perception. The latter is relatively simple to understand and corresponds to the perceived resource availability computed as the mean potential exchange rate per unit of area (total leaf or root area) and per hour (the hourly measure is used instead of daily measure to simulate the ability of plant to perceive the photoperiod). This is an easy way of taking into account one aspect of

CONDITION ESTIMATION

seasonality without complicating the model. However, it also reduce the range of memory and its impact to determine the phenotype, as an additional information would be needed to define the optimum phenotype: the day length).:

$$light_{exp} = \frac{transp}{exchangearea_{ag}} \quad (4.23)$$

$$water_{exp} = \frac{Wpup}{exchangearea_{bg}} \quad (4.24)$$

$$(4.25)$$

The former is related to the species (or group) history and result from processes of selection and acclimation. It is the default projection of resource availability when the plant is not plastic.

$$light_{est}(t + 1) = (1 - \tau).light_{exp}(t) + \tau.light_{memory}.daylength(t + 1) \quad (4.26)$$

$$water_{est}(t + 1) = (1 - \tau).water_{exp}(t) + \tau.water_{memory}.daylength(t + 1) \quad (4.27)$$

Because these are supposed to be expected conditions for the future, other formulation can be used instead of an average that is likely to introduce a lag in estimations. For example the following equation allow for a more stable projection that better fits the slower process of plant physiology adjustments:

$$light_{est}(t + 1) = ((1 - \tau_{react}).light_{exp}(t) + \tau_{react}.light_{est}(t))((1 - \tau_{amp}) + \tau_{amp}.light_{memory}).daylength(t + 1) \quad (4.28)$$

with τ_{amp} and τ_{react} being respectively amplitude and reactivity where only τ_{amp} is used in the first equation. Such solution could limit sensitivity and phenotypic instability. IN addition, such formulation would also better capture the accumulation of stress signals and would lead to a softer and more stable phenotypic shift.

The estimation of external conditions as expressed here is then used to select the best allocation scheme during the allocation process. Limited here to levels of two resources (light and water), this estimation equation could be extended to other mechanisms such as herbivory risk, frost risk, humidity impact on water pressure deficit.

Allocation is primordial in plant development and ontogeny. The following paragraph detail the implementation of the plastic allocation in *MountGrass*.

ALLOCATION

Maturity: For most of plants the development cycle is divided in two phases of different durations: the vegetative phase when plant growths organs to gather resources and product OM, and the reproductive phase when plant take advantage of these organs to accumulate carbon and invest them in reproduction mechanisms. Plants are considered mature (they switch from vegetative to reproductive phase) in *MountGrass* when the phenologic variable has reach a species specific threshold. The phenologic variable can be either the age, the height, the biomass, degree.days, in the current version total living biomass is used as trigger for reproductive phase.

Allocation to supporting tissues: Even-though grasses do not grow tall vegetative parts like trees, some grow vertically and they are exposed to stronger

winds than most of forest. Therefore they need structural supports¹. Not all grasses grow stem, but they'll have stronger central vein in their leaves to structurally support the weight of leaves. In addition shoots and roots also need supporting tissues for water transport, for this reason the minimal mechanical support needed is calculated as a function of total living biomass:

$$\text{support} = \alpha \cdot (BM_{ag} + BM_{bg})^\gamma \quad (4.29)$$

where α and γ are allometry coefficients.

At each time step we must determine what fraction of new OM will be allocated to tissues growth while the remaining will support these need tissues. This leads to an optimisation problem numerically solved by the function `uniroot`.

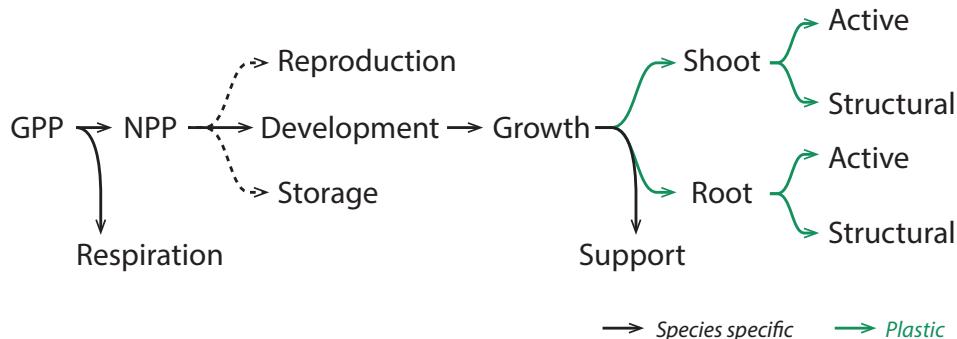


Figure 4.14: Allocation of produced organic matter to different processes and pools.

Allocation to organs: Allocation of produced organic matter is central in vegetation as it shapes the plant and define the strength of the different organs. There are multiple ways to model the distribution of produced organic matter between the plant organs. We believe that such mechanism has great impact on individual development and response to external conditions, and so on community dynamics. To explore the role of this mechanism, multiple options are implemented. The different allocation algorithms are summarised in table 4.3.

There are two major components in the allocation algorithm:

- the objective function;
- the plastic dimensions.

The *objective function*: it is the function that give an fitness estimation or gain metrics for any given phenotype. This function is used to compute the optimum phenotype (phenotype at which the function is evaluated at the maximum value), or rank alternative phenotypes².

The *plastic dimensions*: they are the dimensions along which the individual can move. The space defined by these dimensions is the phenotypic space within which each individual plant can look for an alternative phenotype. They do not necessarily fully define a phenotype since some dimensions of the individual's phenotype can be fixed³.

The objective of this step of the model is to solve the objective function with the unknown variables being the plastic dimensions (RSR, SLA and SRL). In case of simple equations an analytical solution could be used to find an optimum⁴.

² in this case, if not all possible phenotypes are tested, the solution might be only a local optimum. This is the case in *MountGrass* .

³ either by shared parameters of species specific ones.

⁴ under the condition that such optimum exists. The design of the model should ensure that.

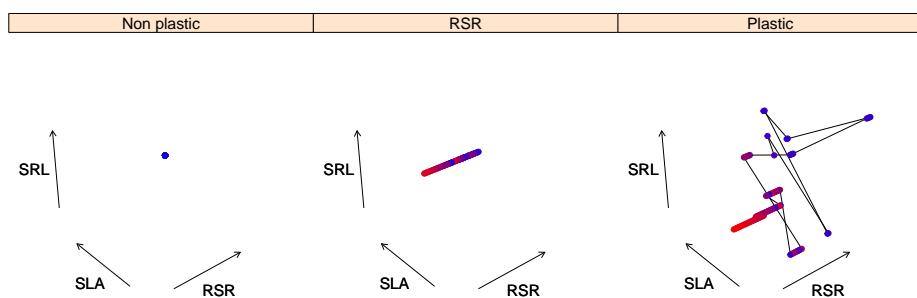


Figure 4.15: Trajectories of a plant in the trait space depending on the plastic dimensions explored.

However, because the analytical solutions are already non trivial and the model is likely to evolve, a numeric solving method is adopted. **Need to detail the random algorithm.**

Also make a note on multiple optimum and the choice for a 'gradient descent' type of algorithm. Also sensitivity at early stages

Algorithm	Objective	variable RSR	variable SLA-SRL	stochastic
No plasticity	—	○	○	○
Equilibrium	functional eq.	●	●	●
Eq-Fixed	functional eq.	●	○	●
Optimisation	instantaneous gain	●	●	●
Optim-Fixed	instantaneous gain	●	○	●

Table 4.3: Allocation algorithms implemented in *MountGrass*

No plasticity allocation: this allocation is very similar to classic vegetation model where the biomass is allocated to the different carbon pools according to species specific parameters. But *MountGrass* differs from other models by the order of the different steps of growth. In this model, the senescence comes between the allocation step and the resource competition-production steps ¹. The partitioning coefficient are directly computed from species default trait to maintain the phenotype after senescence.

Fixed trait allocation: The fixed allocation supposes the allocation on OM to maintain trait values to fixed species specific values. The shoot:root ratio may however change to maintain functional equilibrium. The shoot root ratio is derived from the following equation of the functional equilibrium:

$$SLA \cdot BM_{ag} \cdot light_{est} = SRL \cdot BM_{bg} \cdot water_{est} \quad (4.30)$$

$$\frac{BM_{ab}}{BM_{bg}} = \frac{SRL}{SLA} \cdot \frac{water_{est}}{light_{est}} \quad (4.31)$$

where $light_{est}$ and $water_{est}$ are the estimated resource availabilities.

Plastic trait allocation: Another approach to allocation is to try to optimize phenotype based on a fitness proxy. This proxy can be the sum of NPP, tissue turn-over loss and plasticity cost. But in a complex model like *MountGrass*, plant performance is function of multiple aspects:

- individual organ efficiency;
- relative mass of each organ;

¹ see plastic allocation algorithm for explanation

- balance between organ water exchange activities.

And this could be extended to herbivory or frost risks. To take into account all these components, and take advantage of having all processes already made explicit by the implementation in the model, the daily processes of senescence and production are recalculated according to the **estimation of conditions** and the plant phenotype. This function is used to rank different alternative phenotypes (algorithm detailed below).

Plastic trait equilibrium: An alternative approach can be easily derived from the previous one and extend the principle of the first: the functional equilibrium with plastic traits. This approach consists in using the same algorithm as before but rank phenotypes with a function negatively correlated to the difference between estimated shoot and root activity. Such mechanism would nonetheless require the algorithm to look for close solutions within the allocation space to avoid convergence or drift from species strategy. Having non zero cost of plasticity in this approach should limit the drifting of the plant phenotype.

Fixed trait optimisation: This algorithm takes the idea of the optimisation algorithm but limits the plastic traits to the RSR ratio. If we can expect similar response than the fixed trait equilibrium if we suppose that the equilibrium is the main aspect of plant performance, global efficiency being considered in this case the result may vary.

Alternative phenotypes are computed from the actual phenotype and random uniform distribution of available organic matter to the main active and structural carbon pools of the plant.¹ ... This algorithm has the advantage of being relatively cheap compared to other optimization functions, however, its performances are variables and it is very sensitive to the number of samples used. As a consequence there is a trade-off between model stability and performance as a function of the number of samples (*i.e.* alternative phenotypes) considered.

PLASTIC ALGORITHM

¹ talk about the order senescence production, and the way exchange rates are computed.

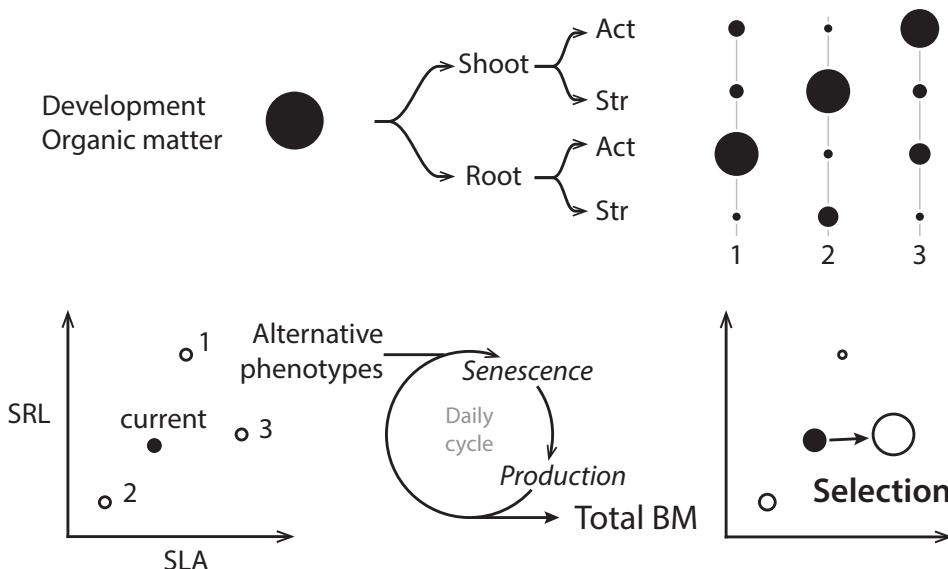


Figure 4.16: Algorithm for the evaluation and selection of randomly generated alternative phenotypes.

The limits and costs of plasticity have long been discussed in the related literature. If *MountGrass* is intended to be used to examine ecological costs and limits, it has to include physiological aspects of plasticity limits. There are two physi-

PLASTICITY COST

ological processes involved in the mechanism of altering a phenotype based on changes in external conditions: sensing and signalling. 'Sensing' relates to the capacity of the individual to perceive environmental conditions. This is related to the capacity of the individual to perceive the environment and should, therefore, be considered constant over time. To take into account the cost of precise sensing, the first component of the plasticity cost is proportional to τ .

The other component is related to the capacity of the plant to transmit this knowledge of conditions to change the development plan toward a new phenotype. This cost is proportional to the carbon-based distance (calculated as the difference between proportion of active tissues) between the default phenotype and the alternative (during allocation algorithm) or current phenotype.¹

Plasticity cost is the sum of both component and is proportional to the total biomass since most of the tissues should have the appropriated cell machinery and are affected by plasticity.

¹ We could imagine cost based not on the default, but the previous phenotype, but it would have led to large phenotypic shifting and convergence.

$$pc_{maintenance} = (1 - \tau) * pc_m \quad (4.32)$$

$$pc_{plasticity} = d_{traits} * pc_p \quad (4.33)$$

where d_{traits} is the Euclidean distance between default phenotype and the alternative phenotype in the space defined by the proportion of active tissue for shoot and for roots.

Plasticity in trait suggests that trait values are modified in time. Because plants are described by single values (e.g. one SLA value for all leaves), this values must be updated after the plastic allocation. This values could be updated as the average of old tissue value weighted by old biomass and new tissue value weighted by the freshly produced biomass. This, however, would work only if active on structural tissues ratio linearly linked to others traits. This is not the case, it is then simpler to consider that organs have uniform active and structural distribution. This hypothesis suggests that whenever the allocation scheme change, old tissue reallocate their own biomass to follow the new scheme. Nevertheless, to avoid full plasticity allowed by this hypothesis, the changes in trait carbon pool sizes are limited by the produced biomass available for plant development.

following the following survival probabilities:

From this, supposing homogeneous distribution of active and structural tissues within an organ allows to directly link the size of the carbon pools to average traits by the following relationships:

$$SLA = \frac{1}{(th.pact_{shoot}.\rho_{as} + th.(1 - pact_{shoot}).\rho_{ss}).V_t} \quad (4.34)$$

$$SRL = \frac{1}{(sr.pact_{shoot}.\rho_{ar} + sr.(1 - pact_{shoot}).\rho_{sr})} \quad (4.35)$$

Senescence is the process of ageing of tissues. This process usually occurs at the scale of an individual organ (e.g. a leaf), however, *MountGrass* does not consider organs independently because it would be complex and computationally expensive to follow multiple leaves and roots for all individuals. So the process is considered homogeneous over all tissues. To emulate the senescence process senescence is calculated from the tissues lifespan, giving :

TRAIT UPDATE

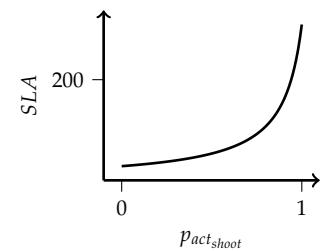


Figure 4.17: Specific Leaf Area as a function of the proportion in active tissues in shoot

SENECENCE

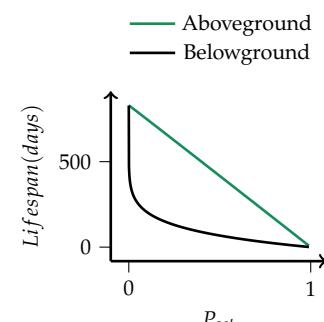


Figure 4.18: Lifespan of organs as a function of proportion of active tissues

$$sen_{leaf} = \frac{1}{LLS} \quad (4.36)$$

$$sen_{root} = \frac{1}{RLS} \quad (4.37)$$

Because *MountGrass* does not contain any mechanism preventing plant from growing only active tissues¹, it is necessary for this cost function to make this strategy unreliable. This is then expressed as follow:

$$LLS = LSs_0 * (1 - p_{act_{shoot}}^{LSS_1}) \quad (4.38)$$

$$RLS = LSr_0 * (1 - p_{act_{root}}^{LSr_1}) \quad (4.39)$$

where LLS and RLS are respectively the leaf and the root lifespans calculated as negative log-linear relationships with the proportion of active tissue.

Root senescent tissues disappear from the system. Information about senescent aboveground biomass is stored, but senescent biomass effect of light competition is ignored in this version because as it is implemented senescent tissues appear early in plant development and have large negative effect on light absorption.

To the natural senescence and artificial cost of having only active tissue, an additional component can be added to the turn-over rate: the negative NPP. In case of negative NPP, the biomass will be taken from the already allocated following the shoot:root ratio. This can lead to a lower overall productivity (negative growth during unproductive periods) but also changes in the equilibrium if tissue have different efficiencies.

Death is modelled as in Reineking [Rei+06]. Age and desiccation (negative NPP) are the two reasons why a plant can die. The two death mechanism are simulated by independent random lotteries following the following survival probabilities:

$$P_d = \exp \left(- \left[\left(\frac{des}{\alpha_d} \right)^{\gamma_d} - \left(\frac{\max(des - 1, 0)}{\alpha_d} \right)^{\gamma_d} \right] \right) \quad \text{if } NPP \leq 0 \quad (4.40)$$

$$= 1 \quad \text{otherwise} \quad (4.41)$$

$$P_a = \exp \left(- \left[\left(\frac{age + 1}{\alpha_a} \right)^{\gamma_a} - \left(\frac{age}{\alpha_a} \right)^{\gamma_a} \right] \right) \quad (4.42)$$

State of dead individuals is stored until the end of the season when seeds are stored in the seed bank. Seeds of dead individuals then join other seeds.

Sexual & clonal reproduction: reproduction is handled at the end of the season. To limit the number of parameters reproduction is limited to the division of the invested biomass in reproduction by the species-specific seed biomass into a round number of seeds (the number of seed per plant could also be a differentiation axis). Clonal reproduction is not explicitly represented but can be mimicked with bigger seeds and by adding a dispersion process around the parents. The seeds then are added to a potential seed-bank. This potential seed-bank is sampled, after eventual invasion, and merged with the existing seed-bank.

¹ it was intended to make the WUE negatively correlated to the amount of structural tissue per area.

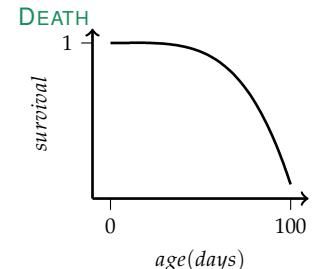


Figure 4.19: Age related survival probability function

Persistence Some grasses are perennial and persist over the cold season. This is allowed in the model by investment in storage tissues instead of reproductive tissues. At the end of the season, marked by the first snowfall, these plants (with non-null storage biomass) lose their living and supporting biomass, but will regrow from a large pool of store organic matter.

Explore management effect on the community is one of the aims of the *MountGrass* GRAZING/CUTTING model. The management of mountain grassland will be explored only of the aspect of biomass removal, as productivity changes can be explored by changing the parameter values as the nutrients are not explicitly modelled. The management sub-model is not detailed here but it is based on the mapping of biomass and target trait (e.g. the fraction of structural biomass as a proxy for digestibility). Both cutting and grazing can be modelled but require management plan in the form of calendar of management operation and a cutting height or harvest objective.

4.4 Limitations and problems

4.4.1 Link to the real world and data

The generalized framework introduced in *MountGrass* allows to create a rich community in a high number of dimension strategy space, it, however, comes with downsides.

One of the first problems is that some parameters (not explicitly detailed here) are hard to access (e.g. tissue density of active, or structural, tissue). It makes the calibration long as the incertitude for some parameters is very high. This is problematic when calibration is made difficult by a large execution time (see subsection below).

Another issue with such model is that the high dimensionality of the species strategy space allows a lot of different strategies that are not viable. This could be overcome by selection mechanism over multiple plots, but again require a lot of simulation. Moreover, there are dependencies between viable strategies and parameter values that make it hard to restrict meta-community to viable species to set-up calibration runs.

It is possible to extract summary statistics from the model output and compare them to information from collected data making calibration and community analysis easy. However going from the data to feed the model is harder, indeed without a great knowledge of a species it is hard to define its representation within the model framework. To do so would require the knowledge of the plasticity capacity to set the reactivity, anatomical traits to define default ratios of active over structural tissues, and climatic niche to define the *a priori* estimation of external conditions. Without making a direct association with real species, it is possible and interesting to try to reproduce some strategies and explore their response to various conditions.

4.4.2 Technical problems

The model is implemented in R with some limiting function using RCPP to speed up the process. Simulations are fairly slow compare to theoretical C++ equivalent code. The main problem is the choice of the data structure. Indeed agents are stored in data.frames that are often modified with the `mutate` function, that makes the implementation much easier and the code readable, but slow down the execution due to constant condition checking on operations. This makes calibration routine methods almost impossible to use as they demand a very number of runs to be efficient.

The slowness of the model also limit to simple algorithms for the research of favourable positions in the allocation space.

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response of these species to two cut frequencies and two N fertilisation levels in monocultures and in mixtures in terms of productivity, plasticity and abundance. In first time, a model hypothesis concerning the leaf C:N stoichiometry has been validated. This leaf photosynthesis coordination hypothesis states a co-limitation of photosynthesis by light-driven and dark biochemical reactions. It has been tested by using a database of 31 species belonging to 6 plant functional groups and growing in different environmental conditions. This hypothesis explained without bias 92% of total variance of leaf nitrogen content per unit leaf area by the variations of three leaf photosynthetic traits. The model equations of substrates allocation between leaf structures and leaf photosynthetic proteins are therefore validated and calibrated. In second time, functional traits linked to root N acquisition and shoot N utilisation (N productivity efficiency and N residence time in tissue) have been measured in field monoculture on 13 species. We showed mechanistically the fundamental relationships linking root and shoot traits (size vs physiological activity specialization axes). Moreover, we highlighted interspecific trade-offs between: i) the root uptake capacities of NO_3^- and NH_4^+ and ii) root area developed in resource patch and root N uptake. These results allowed the integration of root and leaf traits implied in N plant strategies in the calibration of GEMINI for each grass species. Once the model development completed, the simulations showed several emergent properties: 1) after defoliation and nitrogen deprivation, the plastic adjustments of relative size of structural compartments and of their physiological activities restore the functional balance leading to a colimitation of plant by light, nitrogen and CO_2 ; 2) at equilibrium state, the size and the tiller density simulated by the model covary according to a -3/4 power coefficient. The model allows the simulation of vegetative production variations between species and between two cut frequencies and two N fertilisation levels both in monocultures and in mixtures. The observed ranks of grasses relative abundance are well predicted in different six species mixtures. Finally, the model simulates a positive biodiversity effect on the production of 6 species mixtures, which over-produce in comparison of each species in monoculture with the same initial tiller density. When the model is simplified, its prediction ability is degraded. The actual version of the model gives interesting perspective in terms of fundamental question in community ecology and in functional ecology. We provide an application example by investigating the origin of covariations between morphological traits observed in natura. For four traits representative of functional strategies of 13 grass species, a systematic study in 4D space built by these traits showed that: 1) the measured traits value maximizes the simulated growth for each of these species; 2) the individual plasticity observed in response to N deprivation maximizes the simulated growth. These results increases the understanding about the constraints imposed by intra-and-inter-specific trade-offs on the performance and the plasticity of these grass species across resource gradients. PhD thesis. Université Blaise Pascal - Clermont-Ferrand II ; Université d'Auvergne - Clermont-Ferrand I, June 2009. URL: <https://tel.archives-ouvertes.fr/tel-00725487> (visited on 11/12/2014).

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IV

INDIVIDUAL PERFORMANCE: STRATEGY AND PLASTICITY

1 MODEL PROPERTIES AND INDIVIDUAL RESPONSES

The modelling framework developed in previous chapter offers multiple options to explore the effect of phenotypic plasticity on plant growth, and later plant community dynamics. Before investigating the effects of such mechanisms on complex systems dynamics, it is important to have a deep understanding of the model behaviour at individual level. As explained in introduction, the relationship between resource and individual plant growth is the base for plant interactions, abiotic filtering and coexistence mechanisms. This chapter of the document focuses on the calibration and exploration of the model for isolated individuals. The results of the simulation experiments exploring diverse aspect of resource-plant growth relationship will be interpreted at individual scales, but I will also attempt to extend conclusion to higher level mechanisms.

The first part of the chapter is dedicated to the parameter filtering process, the sensitivity analysis and basic model behaviour. Then follows the exploration of plant performance as a function of plant strategy and resources levels and dynamics.

1.1 Parametrisation and sensitivity analysis

Calibration, or , is an essential step in the development of an agent-based model. ABMs are often characterised by multiple processes, and though parameters, at individual levels. The results of these processes (depending of parameter values) from numerous individuals combine to produce the group or community behaviour. Because there are interactions between the processes and between the agents, the overall behaviour of the group (often the subject of interest) is sensitive to these parameters. For the same reasons, an incredible variety of results could be produced with ABMs if the parameters where not chosen in order to produce sensible responses to simulated conditions. The aim of the calibration is to determine, from the *a priori* knowledge of the processes and parameters, and the comparison with data, the best values for the model parameters. This step often goes along with a sensitivity analysis that determine the relative sensitivity of variables of interest to specific parameters.

Because of their nature, ABMs often model processes for which the parameters are either unknown, or hard to access (because at the individual scale). In such cases, advance calibration techniques like pattern oriented modelling[hartig; Gri+05] can be developed. However, such method require a high number of simulations and relatively precise simulation parameters. Because the implementation in R makes the model relatively slow, and because available datasets, despite being very interesting lack information on sensitive parameters, a less robust but less expensive approach is chosen: at the individual scale. The fo-

cus of the part of this work on the individual growth, and the will for more individual-centric approach also support this choice.

For similar reasons of computational cost, the is realised *a posteriori* on calibration runs.

1.1.1 Method

Pot data consists in total biomass and root shoot ration (RSR) data of 11 species grown in pots by Peterson and Billings [PB82]. This dataset has the advantages of being grass species grown in a described steady environment with two conditions of watering with measures of essential components of growth: biomass and RSR.

POT DATA

Simulated plant grow in square pots 9 cm wide and 12 cm deep. The soil is characterised by the following parameters: critical soil water content: $0.1m^3.m^{-3}$, and saturation water content: $0.1m^3.m^{-3}$. Simulation time of 111 days of 15 hours is divided between the growing phase of ... days, followed by the treatment phase when plant are water (soil saturation) either once a week or once a day. The light level and water influx are simulated with water event of ... mm and lighting of ... Watts per square meter. Plants have default geometry parameters and reproduction is ignored and I assume plants do not stop their growth.

POT SIMULATION

The whole filtering process has been implemented in R. Model parameters are sampled following the LHS method (from `lhs` package) within parameter ranges (described in table ??) defined both thanks to the literature and constraints dictated by desired behaviours from the model. When necessary the sample is log transformed. Because of strong relationship between exchange rate parameters and cost of exchange area, exchanges rates parameters are expressed on a mass basis for sampling then transformed into an area basis for the model. To avoid extreme RSR ratios, the ratio between the mass based exchange rate parameters is limited between 0.1 and 10.

PARAMETER FILTERING PROCESS

As explained in previous chapter, species specific parameters are requited to model plant growth. These parameters are sampled at the same time that the parameters of the model, according to ranges detailed in table 4.2.

Once the parameters generated, a first filtering is applied to save simulation time and avoid unrealistic trait values. Compute initial trait values considered out of range (see table for ranges extracted from LES data [Wri+04] in alpine biome) are excluded.

These two steps lead to the creation of a list of n independent parameter sets that are then used for individual pot simulations following Peterson and Billings experiment sett-up.

Results from finished simulations (i.e. plant lives until the end and do not exceed model's internal size limits) are then compared to experiment data species by species. Parameters of logistic distribution are computed from species means and standards deviations for RSR and total biomass. The use of this distribution form is justified by the intrinsic form of RSR measure and the need to reject negative values for total biomass. A parameter set is accepted for one species if it within a 95% range of the calculated distribution for both RSR and total biomass in wet and dry conditions.

The parameter filtering procedure is applied on the three main allocation algorithms: *non plastic*, *fixed-equilibrium* and *plastic-optimisation*.

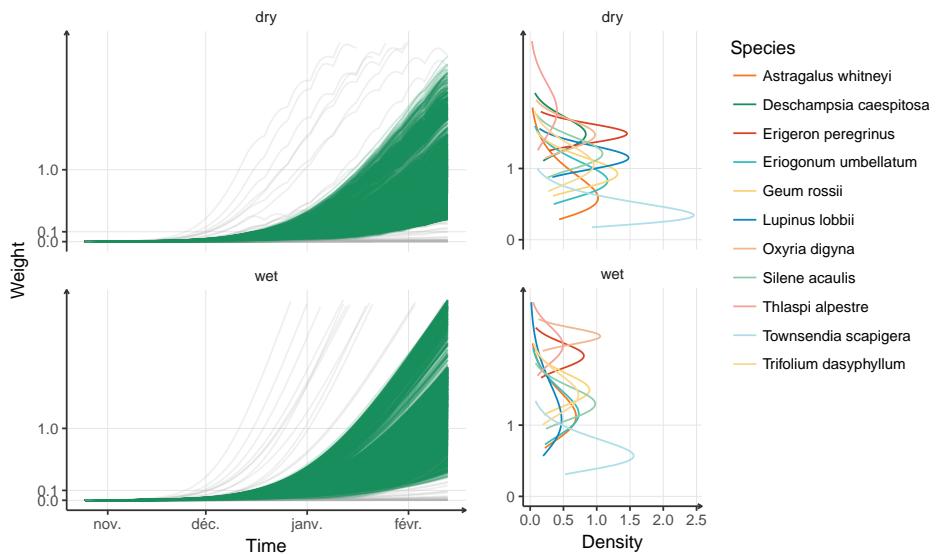


Figure 1.1: Comparison of simulated weights with distribution of weights of real alpine species for contrasting conditions.

Relative importance of variables in the selection process is investigated with the packages `randomForest`. A random forest analysis (depth = 5, number of trees = 300) is performed on a balance dataset composed by all selected parameter sets and a random sample of rejected sets of equal size. Importance is assessed on the results of the random forest.

SENSITIVITY ANALYSIS

1.1.2 Results

Parameter filtering process resulted in the selection of a low number of parameter sets (below 0.2%) for each allocation algorithms (table 1.1.2). This number is below the sum of accepted parameter sets per species because a parameter set can match to multiple species. Not all species contribute to the same extend to the filtering process. *Astragalus whitneyi* accounts for a high percentage of accepted parameter sets, while no parameter set could match 2 species (*Oxyria dignya* and *Deschampsia caespitosa*). The former is characterised by wide distribution in both conditions for the two variables of interest (weight and RSR), while the latter show relatively tight distribution with little overlap between the conditions for the both variables (see figure 1.1 for comparison between simulations and data for total weight).

SELECTION RATE

Despite the low selection rate, a difference can be noted between the *fixed-equilibrium* algorithm and the two other algorithms with a accepted rate of 0.14 % against 0.09% and 0.10% (table 1.1.2). This difference cannot be explained by a significantly better selection rate for specific species, but rather higher rates for all species.

Most of parameter sets are not shared between the algorithms (*i.e.* around respectively and third and a quarter of accepted parameter sets are shared between *non plastic* allocation and *fixed-equilibrium* allocation calibrations), despite that the distribution of parameter values that are not shared are very similar and do not show any clear pattern (data not shown).

Out of the 31 parameters, 6 show graphical response of selection rate (see figure 1.2), and only *u_max* and *P_max* present a possible optimum different from

Table 1.1: Acceptance rate per species for the 3 main allocation algorithms. Because some parameter sets match multiple species, the total number and rate of accepted parameter sets is lower than the sum of accepted parameter sets per species. All rates are given in %.

species	non plastic		fixed-eq		plastic	
	n (2M)	rate	n (2M)	rate	n (200,000)	rate
Silene acaulis	227	0.02	396	0.04	55	0.03
Trifolium dasypphyllum	271	0.03	317	0.03	45	0.02
Geum rossii	51	0.01	72	0.01	12	0.01
Thlaspi alpestre	342	0.03	360	0.04	59	0.03
Deschampsia caespitosa	-	-	-	-	-	-
Eriogonum umbellatum	500	0.05	805	0.08	118	0.06
Townsendia scapigera	593	0.06	930	0.09	107	0.05
Astragalus whitneyi	1570	0.016	2424	0.24	318	0.16
Lupinus lobbii	678	0.07	868	0.09	123	0.06
Erigeron peregrinus	1	<0.01	-	-	-	-
Oxyria digyna	-	-	-	-	-	-
Total	4233	0.43	6172	0.62	837	0.42
Accepted	924	0.09	1416	0.14	200	0.10

limit values. The relative importance of the parameters is better explored in sensitivity analysis.

A total of 12 parameters show relative influence on selection rate for at least one of the algorithm. These parameters are divided between model parameters and species parameters. Species parameters show influence only for the *non plastic* allocation algorithm. Model parameters express relatively similar importance for all three algorithms. The respiration rate of active tissues (r_{-1}) is the most sensitive parameters (see figures 1.2 and 1.1.2). Other sensitive parameters are related to water availability (β_0), organ exchange rates (P_{\max} and u_{\max}) and soil coverage by roots (ρ_{ar} and k_{or}).

SENSITIVITY ANALYSIS

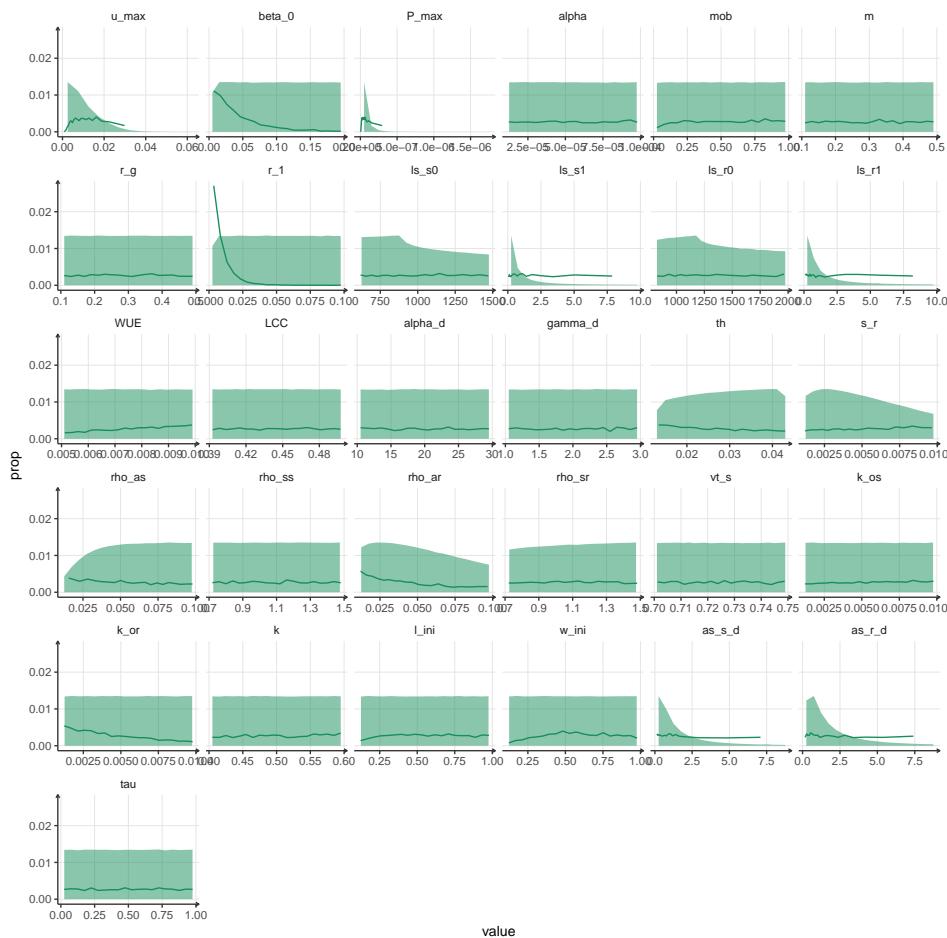


Figure 1.2: Selection rate per parameter for individual growth. Non plastic.

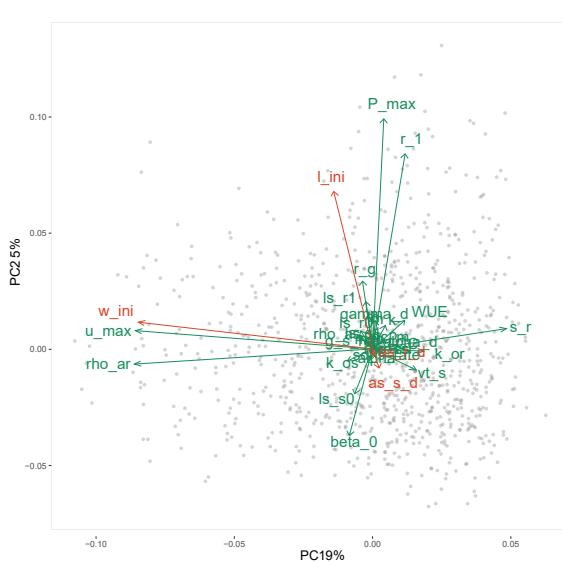


Figure 1.4: Representation of the PCA of parameter sets selected in parameter filtering process on the first principal components. *Non plastic*.

Relative mean decrease accuracy

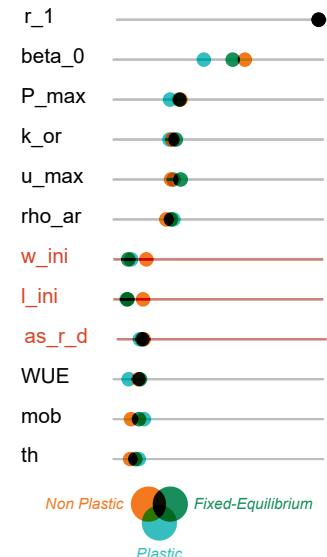


Figure 1.3: Relative importance of main parameters for selection under the three main allocation algorithms: (*non plastic*, *fixed-equilibrium* & *plastic*).

The PCA performed for *non plastic* algorithm only on parameter values reveals that important parameters are also the dominant variables that shapes the selected subspace. The two first axis explain only 14% of variance. The first one is related to the root activity and efficiency (u_{\max} , l_{ini} , ρ_{ar} and s_r), the second is in line with global efficiency and resource availability.

The parameter filtering process is based on individual species, ... Species cannot be distinguished on these two main component space, neither on species specific parameters space (l_{ini} , w_{ini} , w_{ini} & l_{ini} , as_{s_d} , as_{r_d} , as_{r_d} & as_{s_d}) despite small variations in distribution shapes and ranges between species (data not shown).

For each algorithm the response of the two filtering variables (weight and RSR) are plotted against the most important variables in figures 1.5 and ??.

VARIABLE RESPONSES

Total biomass is particularly sensitive to tissue respiration cost (r_1), but also maximum exchange rate parameters. There is a notable difference in growth maxima between the two conditions in favour of wet conditions, in line with observed data. This difference is observed for the three algorithm that differ mainly by the amplitude of the biomass ranges (need data). Growth response curves are similar for all allocation algorithm. Growth is only weakly related to species specific parameters. Total biomass under *Plastic-optimisation* algorithm seems to be more sensitive to variables influencing the exchange area per unit of biomass.

The species specific parameters τ controlling the balance between genetic and environmental control does not emerge as a influencing parameter at the global scale for any of the two flexible allocation rules.

Root:Shoot Ratio (or RMF in figure 1.6) strongly responds to species specific parameters under *non plastic* allocation because the memory parameters (l_{ini} and w_{ini}) are the means plants control their RSR. For other allocation rules, species specific parameters have little control over RSR. Surprisingly, the photosynthetic capacity has stronger influence on the ratio than the root maximum exchange rate.

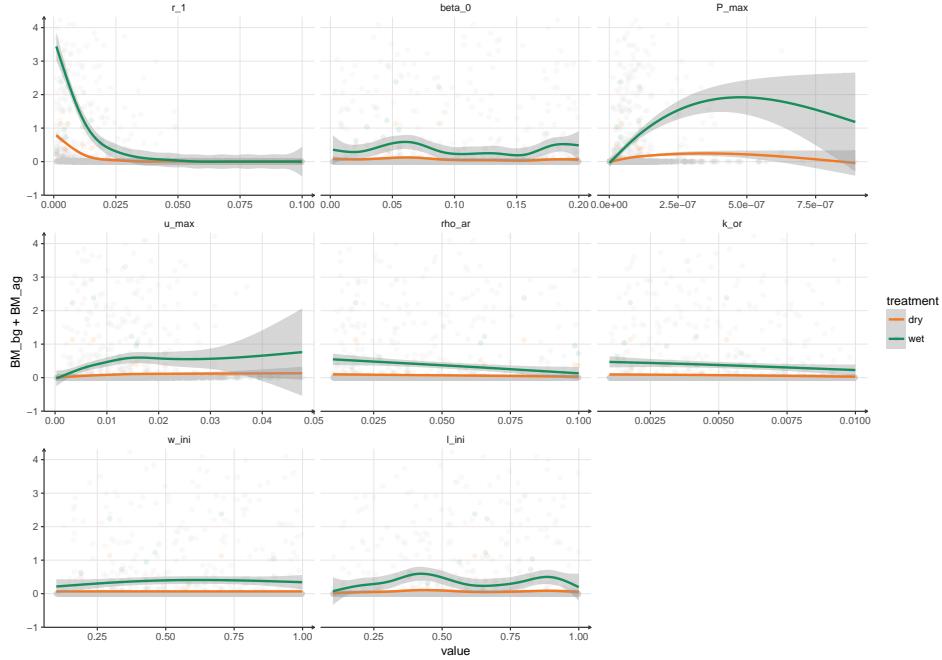


Figure 1.5: Main parameters effect on the total plant biomass. Non plastic. One dot represents a parameter set. Not all parameter set are represented as the y axis is limited around the smooth function (loess). Coloured points represent selected parameter sets in the two treatments (**dry** and **wet**).

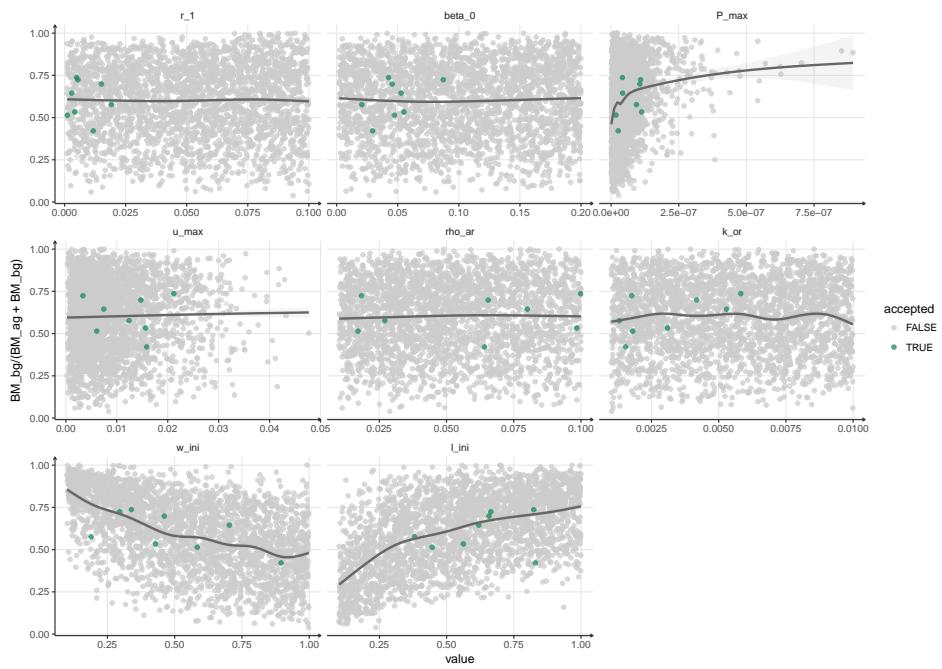


Figure 1.6: Main parameters effect on the total plant Root Mass Fraction (RMF). Non plastic

Little to no difference in RSR is expected for *non plastic* allocation rule since allocation promoted a fixed phenotype, but both *fixed-equilibrium* and *plastic-optimisation* allocation rules allow for changes in RSR. Nevertheless, no stable change in RSR is observed in any of the simulations. Fluctuations are present but consist in stable oscillations between two fixed values (see figure 1.7), synchronized with water variations. These rapid adaptations of the relative proportion of roots denote a high flexibility of plant phenotypes in *MountGrass*.

ROOT SHOOT RATIO AND PLASTICITY

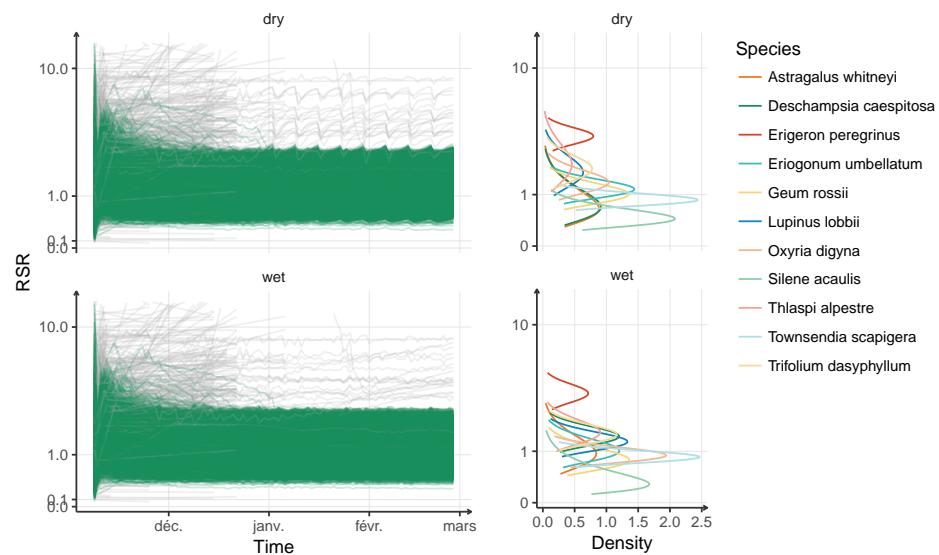


Figure 1.7: Comparison of simulated values of RSR with real species RSR in two contrasting conditions. Because there is no plasticity or ontogeny, the simulated plant do not express any changes in RSR.*Fixed-equilibrium*.

1.1.3 Discussion

The relative low selection rates for all allocation rules highlight the complexity of fitting such complex model to empirical data, despite the relative simplicity of the data. This difficulty seems to lie in two factors: the high number of parameters and the lack of stable changes in RSR. This last point is further discussed in the following paragraphs. Nevertheless, plant growth is reproduced in two contrasting conditions for multiple species, and while plastic algorithms have a greater potential for growth (more high growth rate), this is not systematic and the absence of clear pattern for the most influencing parameters, such as maximum exchange rates and respiration rates, indicates that such high growth depends on a combination of parameter values. I believe that the shape of gain and cost functions along the functional trade-off between active and structural tissues plays a determining role in the growth. A trade-off function with a wider viable range is more likely to be selected as more strategies would grow (therefore reducing the relative sensitivity to species-specific parameters). Considering the exponential shape of the turn-over function (one of the main cost with respiration), the width and height of the trade-off (or net gain function) is probably more strongly linked to the gain functions (exchange rates) and linear cost function (respiration), explaining little effect of parameters related to lifespan (already preselected otherwise). There is a strong dependency between viable strategies (and as a consequence functional potential diversity) and the main trade-off between resource acquisition and efficiency.

GROWTH AND STRATEGY SPACE

Filtering the parameter sets based on all species instead of individually would have been ideal to quantify this link and better calibrate the model. However, such approach would have required many more simulations, when the parameter filtering method was chosen for its low computational cost. Moreover, considering the number of species-specific parameters, fitting the strategy subspace (at least default active tissue allocation parameters, the memory of resources and stability) of 11 species to the data in combination with more than 20 models parameters is near impossible. Ones should have had first determined the relative positions of the species within the said strategy space before any global calibration routine. Nonetheless, species-specific parameters have an influence on model main variables. Memory parameter affected the RSR in the context of *non plastic* allocation rule (see figures 1.7 and ??, while the default proportion of active tissues in roots was an influencing parameter in all algorithms (figure 1.1.2, `as_r_d`). Therefore, they should be analyzed in further simulations within the same set of model parameters.

Change in modelling paradigm. The Bayesian paradigm where the information is contained in data and revealed by the structure of the model. Go for simulation experiment approaches where the model is used as a simulation tool and results as new data. The emerging patterns inform us on the impact of the modelled mechanisms (even if they do not totally match the data). Model as an understanding tool.

Growth is reproduced, but only for one species, not full strategy space.

If the parameter filtering step did not result in the selection of optimum values for all parameters, it provides information on the main mechanisms influence plant growth. Indeed, the relatively high importance of parameters related to water shows the importance of the resource on the model behaviour. Both water availability (water absorption limitation, exchange rate) and root mass and construction parameters are important to match the empirical data. Considering that the calibration relies on experiment data of drought events, it is no surprise that parameters related to water economy show strong influence on the selection rate and model behaviour. In the context where the model has been developed, water shortage is expected to an important factor in community dynamics. In this perspective, the ability of *MountGrass* to reproduce the difference in productivity in both conditions, and the relative sensitivity to water related parameters is an advantage. The link between water resource, species strategy, plant performance and phenotypic plasticity is explored more in details in the following section.

THE ROLE OF WATER

Sensitivity of different variable to the parameters make sense and align with the two criterion of selection (that work with the independence of trade-off).

As mentioned earlier in this discussion, the model is not able to produce any shift in RSR in different water treatment. It is not a surprise for *non plastic* algorithm, but the filter was still applied on this criterion to allow the comparison with plastic algorithm and to be able to measure the improvement in selection rate. However, even plastic algorithms do not show strong enough response to water treatment in term of RSR. A strong and good (in the sense it would have matched the data) is larger in amplitude and more stable in time. Such processes

MORE COMPLEX PLASTICITY?

generally amplify with time, *i.e.* when the number of drought event increases, the response (allocation to roots) increases (relative to default phenotype). Unlike natural systems, plants in *MountGrass* fluctuates between two "states", or phenotypes associates to the dry and wet conditions. The RSR post drought event is reached after the first week without water. This can be explained by two main mechanisms that are related but have contrasting implications. The quickness in response to the changing conditions is allowed by relatively high assimilation rate. If the net growth rate is controlled by the total weight condition during the filtering process, the assimilation rate is not and can be compensated with relatively high turn-over rate. Net growth rate being equal, species with higher assimilation rate will have higher phenotypic flexibility (higher fraction of biomass to invest in carbon pool of choice) than species with lower assimilation rate. This flexibility, similar to reallocation, allows changes in RSR, but not the accumulation of biomass in roots. Unfortunately, both the constant turn-over rate implemented in the model, and the selection toward "wide and high" gain functions limit control on this aspect.

Moreover, the fact that plants are more productive during periods where they may not want to invest in roots strengthen this effect. Indeed, a plant would drift to higher RSR if it was more productive when pursuing the high RSR phenotype than when pursuing the low RSR phenotype. This last point mentions the "will" of the plant, in the context of *MountGrass* this target phenotype is encoded in the projection of external conditions. Because this projection is daily based by design, the accumulation of drought stress is not translated in the internal projection variables of the plant (like it can be with the accumulation of phyto-hormones [need ref]). This limitation highlights a big difference between simulated plants in *MountGrass* and natural plants. While solutions to overcome this problem can easily be imagined(see equation 4.28 in 4.3.3), they would require more parameters and introduce more complexity to the analysis. This model provides a first approach to phenotypic plasticity in grassland models and the formulation of the projection, key element of the phenotypic plasticity, is certainly a starting point for further development. Nevertheless, the differences in response to the parameters between the three allocation rules, despite shared plant functioning, demonstrate the importance of plasticity itself. And simplification of the processes should not be a reason to not explore its effects. The fact that the parameter tau has a relatively small impact on selection rates also support the need to better understand all strategic axis before focusing on the effect of projection. While there are many ways of simulating the phenotypic plasticity, the parsimony is privileged. This simple representation is enough to understand the effects of active plastic allocation in association with the other strategic differences between species.

Bayesian paradigm where the information is contained in data and revealed by the structure of the model. Go for simulation experiment approaches where the model is used as a simulation tool and results as new data. The emerging patterns inform us on the impact of the modelled mechanisms (even if they do not totally match the data). Model as an understanding tool.

MODELLING PARADIGM

Root shoot ratio changes were not captured by the model. The structure of the plasticity mechanisms does not work with the given watering cycle. Needs to add one parameter for reactivity.

1.2 Individual level behaviour and properties

Calibration and sensitivity analysis give information on the main processes of plant growth, but the general effects of the allocation rules on plant growth are not fully identified. In addition, because the parameter filtering processes was limited to individual plants, and the response of species specific parameters dependent on other parameters of the model, the effects of these species specific parameters should further be investigated. The objective of this part is to set better understanding on the role of and species on plant development as basis for interpretation of plasticity effects in following chapters.

The challenge of the framework presented in paragraph 2.2.1 under *plastic-optimisation* is to control the phenotype with the values of the memory. The risk of this approach is to have too tight estimation function of the fitness (or driving function) and to see the convergence of all species (with different memory values) toward the same phenotype (same allocation of active and structural tissues in roots and shoot). The extend to which different species memory lead to different phenotypes under full genetic control (non influence of external conditions) is explored through simulation experiment under *plastic optimisation* allocation algorithm.

1.2.1 Method

The effect of allocation rule on phenotypic development is investigated thanks to pot simulations (see Methods in 1.1) of 100 days in 3 watering treatment: 2mm, 8m and 16mm per day. To avoid drift in the phenotype due to allocation algorithm (see paragraph 2.2.1 on phenotypic determination), simulations where run a first time, then rerun with default specific traits matching traits at the end of the first simulation set. All four algorithms are simulated. To reduce the number of simulations 100 parameter sets are selected randomly within the accepted parameter sets for the *non plastic algorithm*.

ALLOCATION ALGORITHMS

Memory of external conditions plays a determining role in phenotypic development under *plastic-optimisation* allocation rules. The effect of the memory alone (environmental cues ignored by setting tau to 1) on the default emerging phenotype is explored for diverse memories (9 values on the two axis from 0.1 to 1 later scaled to the maximum area exchange rates for model parameter set considered, or 81 values) for each accepted parameter set. The effect of the memory values on the final position of plants in the phenotypic space are visualised by fitting loess curves between memory values and individual trait values.

MEMORY & PHENOTYPE

1.2.2 Results

think of a "showtime" visualisation that shows how growth and traits are impacted by allocation rules and tau.

ALLOCATION RULES

Have the proportion of tissues changing over time

Show the respiration, assimilation and turn-over rates.

Isn't it possible to show these along memory or active/str ratio axis ?

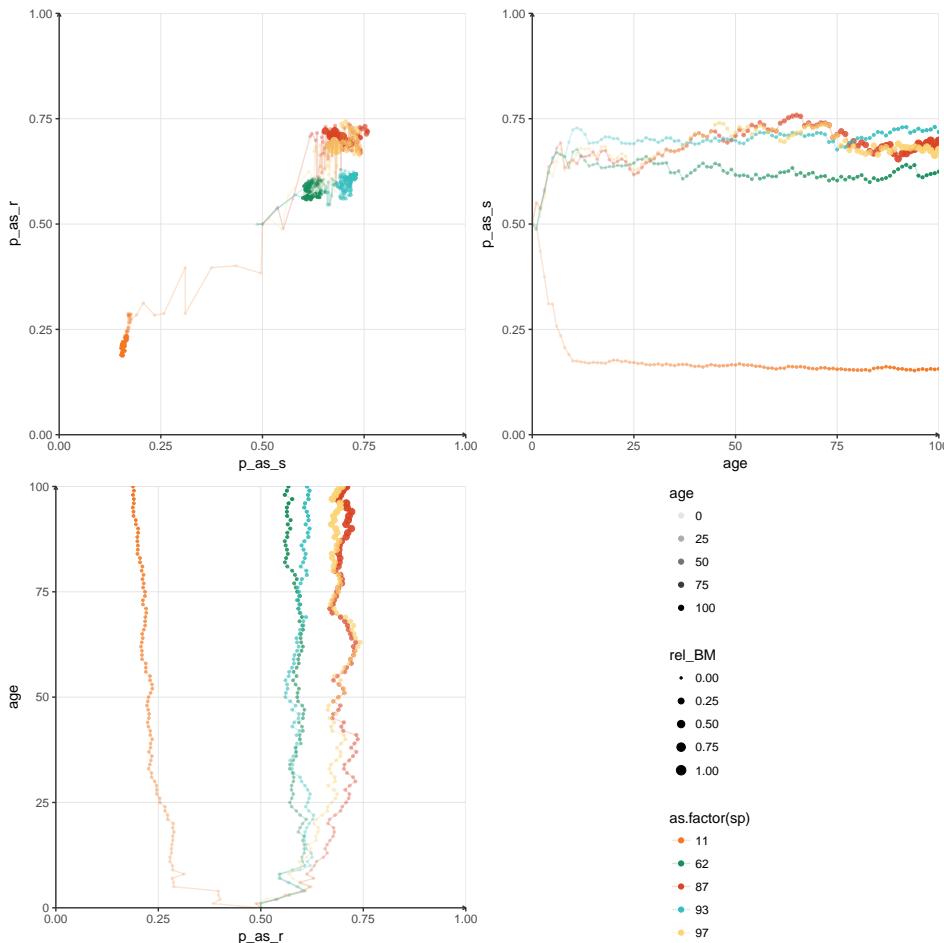


Figure 1.8: Trajectories along time in the strategy space of 5 plants with different memories. After 10 days, all plants have converged toward the estimated optimum.

The kinetic of the phenotypic shift is first visualised for one parameter set on the two main phenotypic axis (proportion of active tissues in roots: PAR and proportion of active tissues in shoot: PAS). From the same starting point the five species show distinct rapid shift toward segregated subspace of the 2D strategy space. The equilibrium point is reached in approximately 10 days for all 5 species. Despite constant memory, variations are visible on both tissue allocation traits of roots and shoot. These variations lead to partial overlap but the five species are distinct on the 2D space.

MEMORY AND PHENOTYPE

The memory of resource availability is a strong enough driver to alter the default phenotype of a species. The effect of the two components of the memory (memory of water availability and memory of light availability) on the three main traits is explored through local regressions. The proportion of active tissues in roots increases to a plateau with increase in water availability memory (figure 1.9). This response pattern is consistent between all parameter sets, but the starting points and slopes may differ. The same pattern is observed between light availability memory and proportion of active tissues in roots (data not shown). The allocation convergence in the root is also influenced by the increase in light availability memory. An increase in the latter leads to a smooth increase in the former (see figure 1.10) with less drastic response than the water. This response is mirrored in shoot allocation response to increase in water availability memory (data not shown). Both organs react in symmetric ways to increases in resource availability. The RSR has a negative log response to water availability memory (positive in the case of light availability memory).

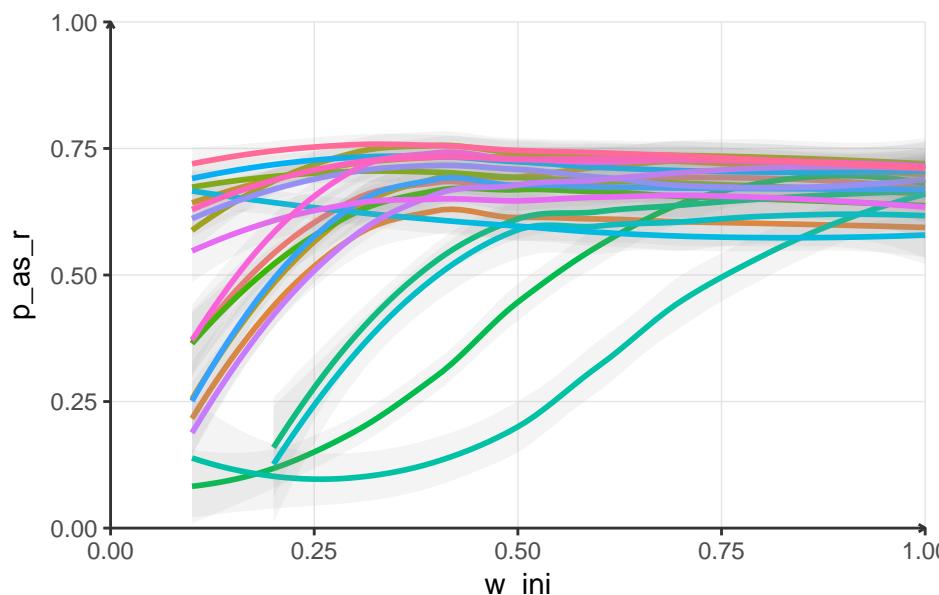


Figure 1.9: Effect of memory of water availability on proportion of active tissues in roots. *Plastic-optimisation*. Each line correspond to a local regression fitted for all memory combinations for a given parameter set. Water availability memory is given in percentage of maximum exchange rate, absolute values may change between parameter sets.

The combine effect of the two axis of plant resource availability memory is observed by plotting the phenotypes (on the 2D space of active tissue allocation) of four contrasting memories for all parameter sets (figure 1.11). There is clear clustering of the four memory profiles, with some overlaps due to the fact that multiple parameter sets are plotted at the same time. The memory of low availability (●) has a much larger distribution area than others, suggesting the relative instability of this profile within the "estimated net gain landscape". Memory of

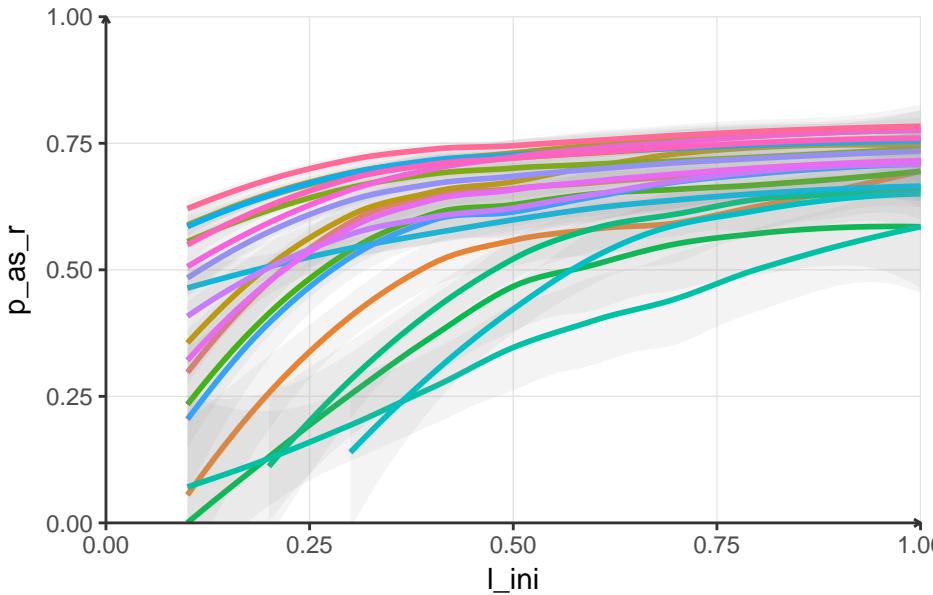


Figure 1.10: Effect of memory of water availability on proportion of active tissues in shoot. *Plastic-optimisation*. Each line correspond to a local regression fitted for all memory combinations for a given parameter set. Light availability memory is given in percentage of maximum exchange rate, absolute values may change between parameter sets.

low availability for both resource drives plant toward very conservative strategies (need some values here) than other strategy. High expected availability of at least one resource increases allocation to active tissues to both organs. This confirms the positive effect of complementary resource (light for roots and water for shoot) of active tissue allocation in organs (see figure 1.10). Because of this, there is no highly unbalance phenotypes with high contrast between organ specific allocation emerging from the *plastic-optimisation* allocation in *MountGrass*. There is general coordination, but the balance between resource availability memories still impacts the position on the 2D, illustrated by the absence of overlap between low light - high water (●) and high light - low water (○) phenotypes. In case of high resource availability and coordination, high investment in active tissues for both organ is achieved(●) and high light - high water), but the range of values is similar than for unbalanced memories(●) and high light - low water (○).

1.2.3 Discussion

rapid convergence.

[ALLOCATION RULES](#)

Cost and gains

Diversity of phenotypes

Crossed and symmetric influence: the respective efficiencies cannot be analysed independently.

Allocation rules are extremely important as they reduce the phenotypic space explore. Without even considering plasticity. Need a good understanding of the performance within the phenotypic landscape. Plus there is a need for alignment between starting phenotype and endpoint. Will also affect how plasticity is driven.

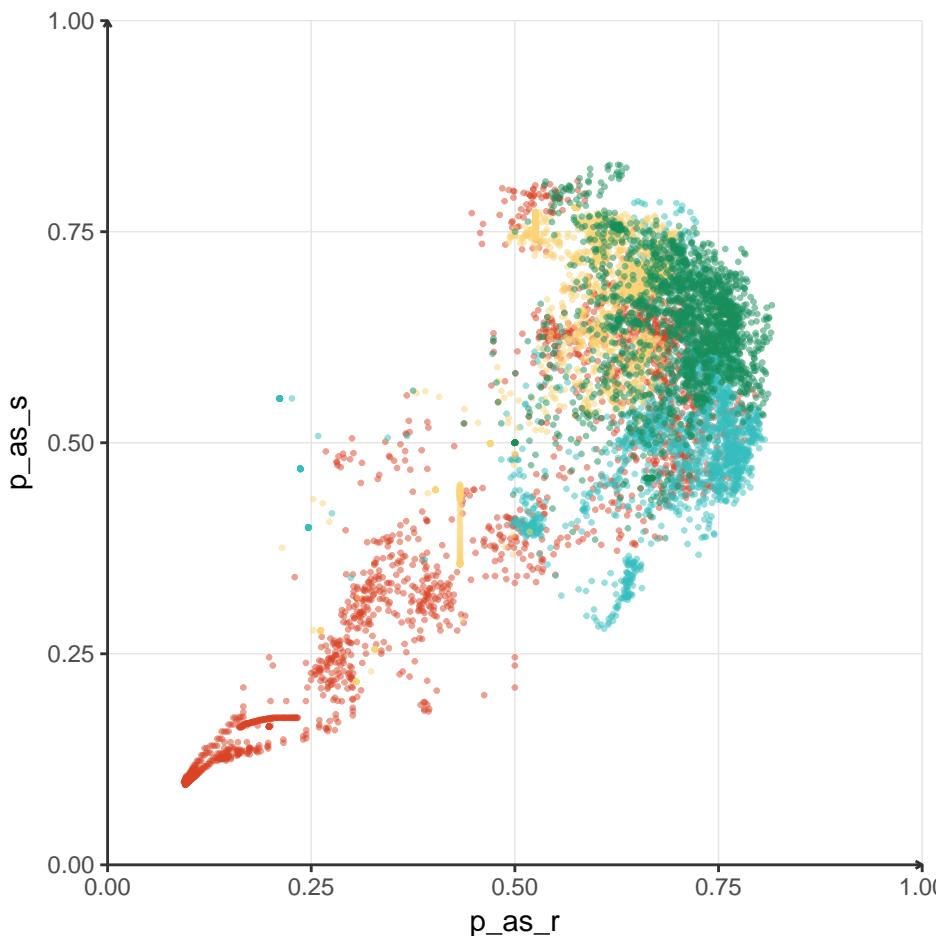


Figure 1.11: Impact of species memory on final phenotype in case of fully plastic allocation. *Plastic-optimisation*. Each point corresponds to a plant phenotype for a memory syndrome for a given parameter set. Colours denote the memory syndromes.

- low light - low water,
- HIGH light - low water,
- low light - HIGH water,
- HIGH light - HIGH water.

... nothing here yet, the idea was to show that the "strategy" of the species conduce to slow and fast archetypes. Should be able to show that with some memory simulations.

FAST-SLOW STRATEGIES

But not equal distribution along the axis probably.

Allocation trade-off allow for strategies from the fast-slow spectrum to arise, independently for shoot and root, in coherent framework. Potential effect of other strategy axis can be analysed alongside this trade-off, even if they affect composite traits like SLA or SRL.

The symmetry and the curves shapes suggest that resource related organ is more sensitive and that "apparent" increase in resource availability promote more exploitative strategy. - what mechanism ?

MEMORY AND PHENOTYPES

It seems that there is greater concentration around high values of active tissues. This is consequence of net gain curves. Is this verified in other allocation rules ? Or is this an artefact ?

The role of memory highlight the expected problem of matching default phenotype with memory: little ontogeny effect (due to high growth and turn-over rates) and problem with distance based plasticity cost (would require a moving cost, instead of fixed reference cost).

For each parameter set the alpha shape of the volume could be drawn to have an idea on how parameters impact potential functional diversity. But no time here to test that.

Memory is a strong enough driver to control plant organ strategy. The effect of overall activity should be studied too and considered if memory is used to determine the default phenotype.)

Role of allocation rule and changes in traits, traits affect strategy and performance, memory lead to different phenotype/strategies (based on gain function), there is coordination, effect of complementary resource. Need to better understand allocation rule and optimum strategy, and convergence and diversity.

I REALLY NEED TO EXTEND THE CONCLUSIONS AND GO BEYOND MY OWN WORK. REFER MORE TO OTHER PEOPLE WORK !!!

2 INDIVIDUAL PERFORMANCE, PLASTICITY AND VARIABLE CONDITIONS

The previous section highlighted the ability of the model to model growth, but also the importance of species specific parameters. While the plasticity mechanism did not replicate to a full extend (stable and higher amplitude) the phenotypic changes between the different conditions, there were some changes both in traits, and in growth leading to a higher selection rate. Considering the importance of species specific parameters and their potential impact on growth,

these differences between plastic and non plastic allocation rules should be investigated in an extended manner. The specific roles of strategy and memory on the multiple components of plant growth need to be disentangled to draw better hypotheses on the role of phenotypic plastic on plant performance and coexistence. The role of resource availability on these mechanisms also needs to be interrogated. The effect of plasticity on coexistence can also be approached with respect to relative performances and contraction of the strategy space.

This chapter tends to answer these questions with simulations of individual plants with diverse strategies and under multiple allocation rules. To simplify the approach and focus on the interaction between species strategies and allocation algorithm, the plasticity will be model as discrete mechanism ($\tau = 0$ for all plastic allocation algorithms).

2.1 Individual performance: between strategy, memory and plasticity

This first subsection focuses on the link between the phenotype and the plant performance. The plasticity and allocation mechanisms can affect both the link between phenotype and performance and the distribution of the existing phenotypes.

2.1.1 Method

Because little differences are found between accepted parameter sets for the three main algorithms, parameter sets selected for the *non plastic* algorithm are used for all algorithm. To reduce the number of simulations but have a measure of the genericity of the observed patterns, 20 parameter sets are selected among the accepted parameter sets for the *non plastic* allocation algorithm. As mentioned in the previous section, the parameter sets have been selected for only one species-specific and therefore an additional step was used to filter out the parameter sets that could lead to high biomass values. For each parameter set, simulations of diverse phenotypes run for 100 days of 15 hours with favourable temperature conditions (20 °C) along resource availability gradient. The parameter sets are selected based on the maximum biomass of all simulated plants. One parameter set is randomly selected for each of the 20 brackets between 0 and 2 grams of total biomass.

PARAMETER SETS

To better understand what make a plant perform in the model, a multitude of phenotype needed to be tested. Tested phenotypes are distributed regularly along the three axis of the strategy space (proportion of active tissues in root, proportion of active tissues in shoot, proportion of roots) between extreme values (respectively (0.1, 0.99), (0.1, 0.99) and (0.1, 0.9)) for a total of 3375 combinations (15^3). Because the RSR is defined by the memory, and in this set of simulation experiments the RSR is defined before, the species memory needs to be computed afterwards. There is an infinite number of couple of memory values that can match a given RSR. Also, the projection of conditions is sensitive to both memory and experienced conditions, therefore the choice of memory can affect the relative sensitivity of species to changes in external conditions and alter the model behaviour. Because the role of memory is not the focus here, and

STRATEGY SPACE SAMPLING

because there is much more focus on the role of the plasticity as a mechanism (as opposed as a strategy with various values of tau), the parameter tau is set to 0. This ensures that only the starting phenotype and the experienced conditions play a role in plant performance.

For each phenotype a pot simulation is ran for 100 days of 15 hours under 4 millimetres rainfall and 120 Watt per square metres and per hour with the 4 main allocation algorithms (*non plastic*, *fixed-equilibrium*, *fixed-optimisation* and *plastic-optimisation*). Two resource levels are tested for each simulations. The low resource availability conditions correspond to a reduction by a factor 4 of resource influx, but the day length was conserved.

To visualise the performance landscape (plant performance relative to biggest plant as function of its phenotype) the performance of best phenotypes are projected against the 3 plans that compose the phenotypic space. Such projections are preferred to 3D alternatives as they work better with static visualisation and when most of the space is occupied. Alternative axis are defined to facilitate the interpretation and description of the performance landscape: the organ strategy plane(PAR-PAS plane) can be transformed into strategy balance (difference between PAS and PAR) and "speed" (in sense of Reich [Rei14])(mean allocation to active tissues).

To study the potential effect of resource availability and or allocation mechanism on the link between strategy and performance, an aggregated measure is designed: the of the phenotypic space is defined as the average phenotype weighted by the relative performance of each phenotype. It can be defined with respect to the initial strategy, or to take into account the plasticity, to the final position in the phenotypic space. Shift of this gravity center within the projection space inform of translation of the performance landscape.

2.1.2 Results

SIMULATION SET-UP

PROJECTIONS

PERFORMANCE LANDSCAPE

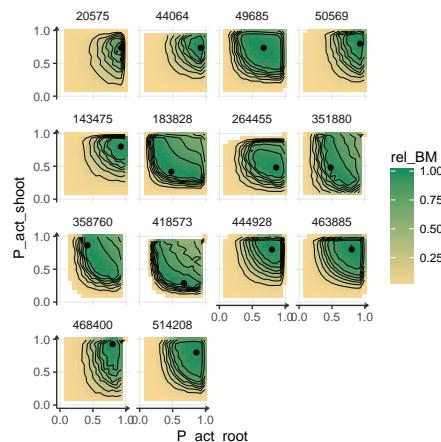


Figure 2.1: Projection of best phenotypes (varying RMF) on the 2D PAR-PAS plane for each parameter set. Points identify the optimums. *Non plastic*.

On the tissue allocation plan (proportion of active tissues in leaves and roots), the best performing phenotypes present a bean shape. This shape suggest that relative importance of organ efficiency is lower than other criterion such as equilibrium and overall performance (see section 3 paragraph 3.2.1 for the discussion

on the components of plant performance). On this plane, the lowest values of plant biomass are characterised by low values of active tissue allocation.

Phenotypes with high active tissue allocation values tend to have lower growth values than phenotypes with similar values for one of the organ and lower value for the other organ.

Projection of the best phenotypes over the three planes also gives information on the importance of the ignored variable on each plane. The greater the discrimination of the subset of best strategies on a given plane, the lower the importance of the ignored plane. The projection on PAR-RMF and PAS-RMF planes discriminate better phenotypes relatively to PAR-PAS plane, therefore the RMF is a more sensitive variable than the allocation factors to active tissues in organs.

If equilibrium is a driving mechanisms in plant performance, for any given strategy (PAR-PAS plan projection) the best phenotypes has a RMF values that guarantee the functional equilibrium. However, for each strategy there is a notable difference between the RMF of best phenotypes and the RMF of phenotypes the closest to the equilibrium. This disparity is positively related to the strategy balance: best phenotypes with higher active allocation in shoot than root have lower allocation to roots than required for functional equilibrium.

Higher resource: contraction of the landscape, toward faster species. Moving optimum and moving gravity center. Transition to optimum shifting and difference between allocation rules.

Biomass is relative to best performing non plastic plant (to remove the general parameter set effect on growth) and compare (within each condition) the effect of allocation algorithm. Plasticity lead to an increase of average relative biomass, especially full plasticity. However, few values above 1, in fixed conditions there is real additional value of plasticity compare to fixed allocation.

A shift of gravity centres can be observed between the two resource levels in all plasticity algorithms. *Non plastic* and *fixed* algorithm show similar trends with an increase of proportion in active tissues in both organs. This change toward more exploitative tissues is consistent and is observable for all parameter sets but one. The *plastic-optimisation* algorithm show drastically different responses of gravity center of phenotypes. There is little change in shoot proportion of active tissues, but a consistent reduction of active tissues in root system, and a reduction of root mass fraction (data not shown). These two responses indicates a net reduction of root activity in favour of shoot activity. Two things must be taken into consideration while looking at these results: (1) the gravity center is computed from final position into the phenotypic space, not the starting position, (2) because *plastic-optimisation* algorithm allows changes in traits that are represented (PAR and PAS), shifts along these axis can be driven by the plasticity mechanisms and not necessarily only performance differences. Similar representation of the gravity center computed from the initial phenotype (not shown) shows similar response for the three first algorithms, and no apparent shift for the *plastic-optimisation* plasticity.

OPTIMUM SHIFTING

Non plastic and *fixed* plasticities respond the same way to a shift in resource availability. However, we can note that the gravity centers have lower proportion of active tissues for *fixed* allocation algorithm compared to the *non plastic* one.

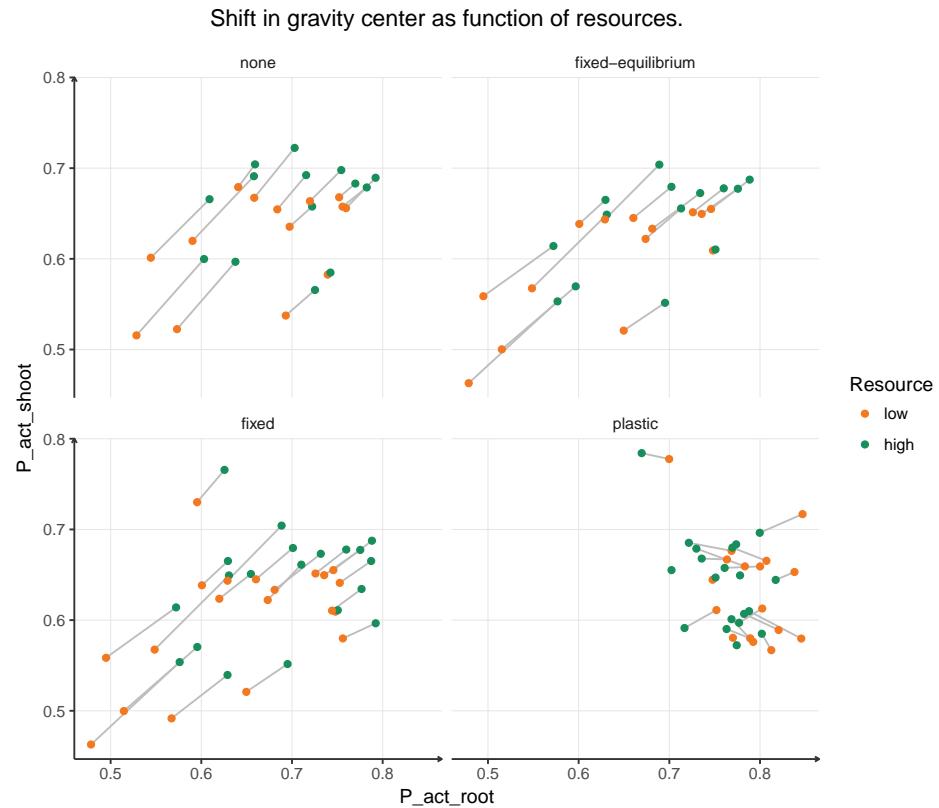


Figure 2.2: Shift on the 2D phenotypic space of the center of gravity as function of resource availability. The center of gravity is defined as the average phenotype weighted by the relative biomass, and characterises the performance landscape. *Non plastic.*

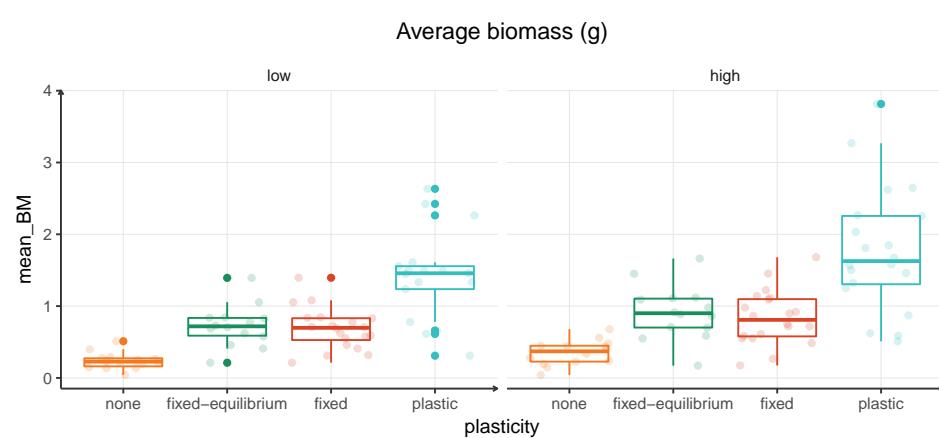


Figure 2.3: Mean relative biomass as function of allocation algorithm and resource level.

Shifts in optimum, is it because plasticity provide more efficient functioning supporting more exploitative strategies, or side result from convergence that do not contain the previous optimum ?

PHENOTYPIC CONVERGENCE

Convergence, relative species diversity and functional diversity.

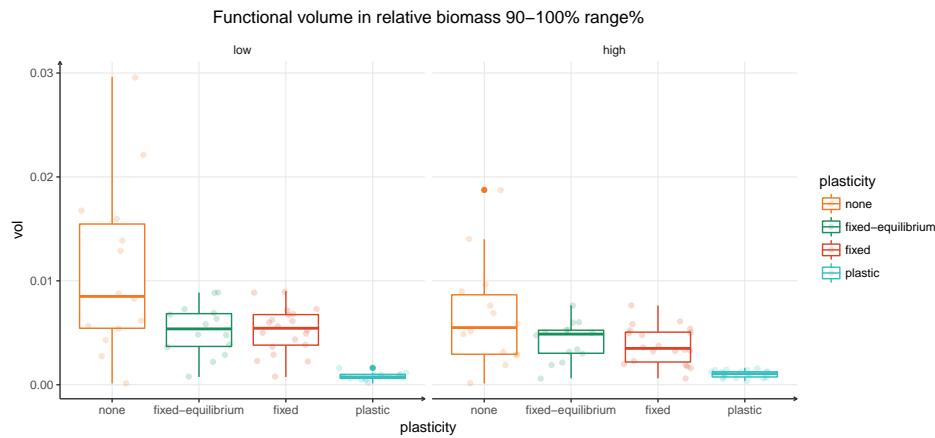


Figure 2.4: Functional diversity as function of allocation algorithm and resource level.

2.1.3 Discussion

To understand how plasticity can play a role, it is important to understand what make a phenotype a good phenotype. In another way it is important to understand what cost do a plant for being wrong.

COMPONENTS OF PERFORMANCE

, overall and overall .

The main thing with equilibrium is the total resource use.

Better too fast than not fast enough.

Explain the memory stuff in previous section: low-low compared to low-high, the second one lead to overall higher productivity (lack of one resource compensated by higher allocation to the related organ) that can support more active tissues.

The role of RMF: controlling variable, more sensitive than PAR and PAR but because bigger impact on balance: wide range on RMF values with similar performance: RMF value in itself is not that important: equilibrium is.

CONVERGENCE TO SUBSPACE

Phenotypic plasticity is often perceived with a species-centric perspective, that is to say, that plasticity is seen as variations in the species mean phenotype. However, in the context of community ecology, it is also interesting to try to see how it not only affect individual species but shape the community distribution in the strategy space. Plasticity relies on changes of default phenotypes toward "better" strategies in the context of the given conditions, therefore it implies that if it exists an optimum subspace (one strategy or an ensemble of strategies) species will converge toward this subspace, distorting the functional space. Environmental variations and plant interactions aside, in a constant environment the is fixed. As a consequence the plasticity benefits to the plant in a static manner, that is to say, it is only a tool to reach a better phenotype where the plant stays in if conditions do not change. This can be related to spatial heterogeneity that would lead individuals from the same species to adopt different phenotype to acclimate to the particular conditions of their spatial situation. It is opposed

to the perception of a more dynamic phenotypic plasticity as a tool for a given individual to cope with temporal variations in environmental conditions. These two aspects are further discussed in the following section, while the effects of the contraction of the phenotypic space are discussed now.

As explained before, plasticity can be seen at the scale of the species assembly¹ as a contraction of the phenotypic space of the species assembly. This contraction has two main effects: the reduction of potential functional diversity and a reduction of growth rate differences. There is here an emerging trade-off between the species diversity, supported by lower fitness differences, and functional diversity, reduced by the contraction of the phenotypic space. However, if the plasticity reduces greatly the potential functional diversity (volume of the whole phenotypic space without considering filtering based on relative fitness), the realised diversity (expressed as the functional diversity of the species within the 90%-100% maximum biomass range) is much less impacted because a large part of the phenotypic space (explaining the large potential functional diversity) has low growth rate in the given conditions. Nevertheless, the reduction of the diversity of expressed phenotypes is greater than it could ideally be. Indeed, in this scenario of "extreme" plasticity ($\tau = 0$) the convergence is important on plastic dimensions where it is not needed to have a significant increase in fitness (see conceptual figure ??). Lower convergence on plastic dimension should lead to less compact phenotypic subspace while keeping relative fitness evenness. In the case of *fixed-equilibrium* and *fixed-optimisation* plasticity mechanisms, this effect is reduced by the sensitivity of the growth rate to the unique plastic dimension (see figure ??). ... About *plastic-optimisation* convergence...

Cost and distance, sensitivity to environmental cues as solutions to this problem.

Because of high convergence of *plastic-optimisation*, no improvement of maximum biomass, but the *fixed* alternative thanks to convergence limited to one phenotypic dimension (RMF) higher biomass: either higher resolution, or improvement due to . The role of dynamic plasticity benefit is explore in temporal variation simulations in the following section.

Somehow I need to talk about the cost of being wrong. Can be observe in the delta heatmap on delta strat and delta w-init: in this case there is less impact of being wrong of memory if you're good with strategy, because your not in different conditions...

Potential effect on diversity: lower functional diversity, increase evenness. Leave highest fitness spot free. Why ? environmental cues or gain function ? Delta between projections ?

Anyway, being good in stable conditions may be useless if cannot survive or keep gain in other conditions. » look along gradient if best species keep their rank.

Plastic-optimisation is characterised by a high convergence of the species within the phenotypic space, high mean biomass but maximum biomass lower than best *non plastic* phenotype, and high potential species diversity. The convergence is expected and explained by the fact that all three traits are plastic, all species (for a given resource level) experience similar conditions leading to the computation

¹ here I draw a distinction between species assembly that refers to all present species, and community that refers to the interacting individuals of the present species. However, some interpretations can be translated to communities.

of the same optimum, and there is no plasticity cost limiting the convergence toward this optimum. This convergence explains both the high potential species diversity, as all species have very similar growth rate, and the relatively high mean biomass because only few species did not survive or had very little growth rate.

However, the fact that this plasticity does not translates into higher maximum biomass is surprising, especially considering the fact that RMF plasticity improves maximum biomass (see figure 2.3). Lag in adaptation is often identified as a limit of plasticity [DSW98; VF05], nevertheless, in a constant resource influx experiment, and considering the high phenotypic flexibility of plants in *MountGrass*, this explanation is unlikely. Another problem highlighted with plasticity is its adaptiveness. Evolutionary speaking, it is hard to imagine the emergence and maintenance of a plasticity mechanisms in one particular context if it is no adaptive, however it could be maladaptive in a new context. Because plasticity is not emerging, but imposed in the context of the model, its adaptiveness can be interrogated. Here adaptiveness do not refer to a reduction of fitness due to plasticity, but to the capacity of the plastic mechanism to define an optimum (or at least better) phenotype. Plasticity as implemented in model has no explicit bias and all mechanisms involved in plant growth are simulated by the allocation mechanism. The sampling of phenotypes is random and could be source of uncertainty, but it is uniform and no consistent drift is likely to emerge from the noise introduced by such sampling. The last aspect of plasticity that can affect the adaptiveness of plasticity is the estimation of conditions. The estimation of conditions is based on conditions experienced by the plant and by definition are exact, therefore the problem lies in the projection of these conditions and how they translate into resource uptake. In *MountGrass* the resource availability is an uptake rate per day and is computed as the resource uptake divided by the exchange area. This resource availability is supposed constant, and plants make the assumption that increasing their exchange area leads to a proportional increase in resource uptake. However, in the case where a plant already absorbs all the available resource, then this assumption is not respected, and the uptake rate per area is lower than expected. This gap between perception and actual resource availability occurs because the plant is not able to perceive that the limitation cannot be compensated by a higher investment in the limiting organ. This behaviour explain a very high investment toward root and root active tissues in low resource conditions under *plastic-optimisation* allocation (figure 2.2). This gap¹ is the origin of as it leads to an overestimation of one resource.

... why not a stronger response in case of *fixed* plasticity ? There should be some ? How is it reduced.

What happen to plastic plants ? Wrong phenotype ? Wrong ? Wrong strategy or wrong RMF ?

This analysis was conducted with drastic parameters of plasticity with plastic plants relying only on their perception of external conditions to develop their phenotype. The different results ... different directions and impact on potential diversity.

Also, some species may not benefit from plasticity, especially if it has a cost, while others can benefit a lot from plasticity.

The contrasting responses of the different algorithms highlight the impor-

¹ this is different from a lag because it is not the result of slow changes in phenotype but comes from a default in the estimation of optimum phenotype.

tance of the allocation mechanism. However, the unique framework implemented in *MountGrass* creates a variety of nuanced responses that are not all explored here. But, the continuous gradient of strategy between species relying on species memory only and species following their perception of external condition should be kept in mind during the interpretation of these results and following.

results from this part

As expected the resource availability and the resource balance are key components of the plant growth, to which the plant phenotype needs to match. Aside from the increase in biomass, an increase in "speed" of optimum phenotypes can result from higher resource availability. This observation is in agreement with empirical data that demonstrate higher SLA and faster physiology in favourable conditions. This aspect was less obvious in the response of species under *plastic-optimisation* allocation that shifted more in term of balance and RMF. This may be due to a change in the relative balance between both resources as their availability (from the plant perspective) are linked to the global resource levels by non linear relationships.

RESOURCE AVAILABILITY

The fact that plastic plants (for *fixed* allocation algorithms) show shifts of optimum strategies toward more exploitative phenotypes, in addition to the *non plastic* optimum shifts, in conditions of higher productivity demonstrate the importance of these strategies for plant growth. However, the extend of this effect of conditions on optimum phenotype is susceptible to vary along a gradient. Indeed, because of the non linearity of relationships between resource levels and exchanges rates, and between exchange rates and growth rates, the link between the optimum phenotype and a resource gradient is likely to be non linear itself. In addition, phenotypic plasticity might also change the sensitivity of the phenotype to the resource level.

Why we need to go for a gradient.

? about what ? Community dynamics ? pp impact of these dynamics ? coexistence of species

GREATER LEVEL DISCUSSION

Subsection conclusion: bla bla bla

2.2 Plasticity and variability of conditions

Question I try to answer: (use of schematics ?) The heterogeneity of conditions is an essential mechanism for plant coexistence. Plasticity is likely to alter the effect of this heterogeneity on plant coexistence and relative performance. The impact of plasticity on this relationship between spatial and temporal of resources (here limited to water) and strategy dominance is explored with the model *MountGrass*.

Effect on optimum strategy: from previous conclusions and hypothesis to simulation method.

Then on diversity: how good strategies perform when it is plastic. Pool of species that exist in different conditions to get rid of the static effect.

2.2.1 Method

Because little coordination, and importance of below-ground resource acquisition (in the results, and in the context) and computational cost - only root strategies.

For each of the 20 selected parameter sets, growth of 400 plants (20 PAR values between 0.25 and 0.95, and 20 memory values between 0.1 and 1) is simulated for 100 days in square pots of 12 centimetres deep and 90 centimetres wide (to avoid quick self-competition) in a temperature of 20 degrees celsius during the day of 15 hours, and 10 degrees during the night. Irradiance is set to the high values of 122 Watt per hour and per square metre.

SIMULATION SET-UP

Spatial heterogeneity of water level is mimicked by a gradient of water influx. The growth of all 400 species described above are simulated for *non plastic* and *fixed-equilibrium* algorithm independently in separated simulations where the water influx is regularly sampled between 0.05 and 7 mm per day (20 values).

SPATIAL HETEROGENEITY

Similar set-up is used for temporal heterogeneity simulations. Because the range of water influx used in the previous simulation is too wide, a lower value is chosen as the mean water influx. This value of 1.3mm per day corresponds to a point around which there are variations in the optimum strategies for most parameter sets. It is also relatively close to average rainfalls in the Alps during summer.

TEMPORAL HETEROGENEITY

2.2.2 Results: gradient of homogeneous precipitation conditions

The effect of allocation algorithm is observed on all species by plotting the position of the *center of gravity* along the watering gradient that translates what part of the strategy spectrum (from conservative to exploitative) benefit from the simulation conditions. Along the gradient, conservative species exhibit higher growth than exploitative species with a median gravity center around ... % of active tissues in roots for the *non plastic* allocation algorithm, and ... % for the *fixed-equilibrium* plastic allocation. In the other end of the spectrum, for watering values above ... mm, the *center of gravity* reaches a high point (median around ... % of active tissues for both algorithms) demonstrating better performance of exploitative species in high resource availability conditions. Plastic (*fixed-equilibrium*) simulations show lower *gravity center* in low resource availability than *non plastic* counter-part.

OPTIMUM STRATEGY

As seen in the previous part, the shift in optimum can be caused by but do not necessarily represent a change in optimum strategy. The effect of plasticity on the optimum strategy is tested along a precipitation gradient. Both algorithms are characterised by rapid shift from more conservative strategies in low water influx conditions toward high proportion of active tissues in root along the increasing rain gradient (figure 2.6). There is no apparent differences between algorithms and the optimum is conserved along the gradient. There is a similar shift with an increase of optimum water availability memory for *non plastic* algorithm.

A lot of effects discussed here emerge because a lot of different memories (equivalently RMF values) are associated to each resource use strategy for roots (shoot active tissue allocation being fixed and shared by all species). Another way of looking at the effect of plasticity focuses on only species identified as the best in

EFFECT ON POTENTIAL NICHE

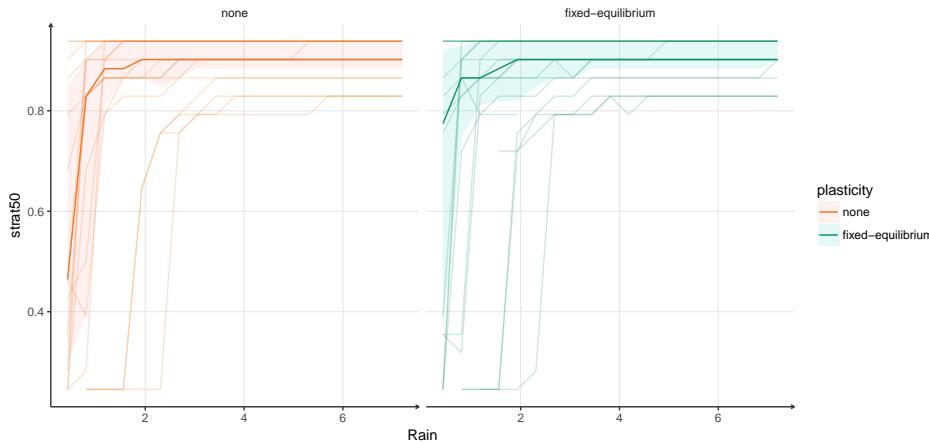


Figure 2.5: Median (dark line -) center of gravity of root strategy along the water treatment gradient for *non plastic* and *fixed-equilibrium* allocation algorithms. The color ribbons mark the band between the 25th and the 75th, and between 5th and 95th percentiles.

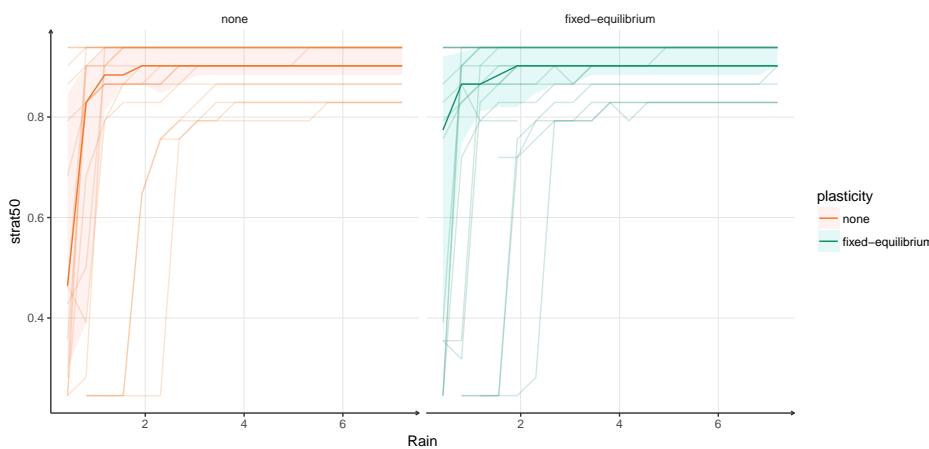


Figure 2.6: Median (dark line -) optimum root strategy along the water treatment gradient for *non plastic* and *fixed-equilibrium* allocation algorithms. The light lines (-) correspond to the 20 independent parameter sets. The color ribbon marks the band between the 5th and 95th percentiles.

at least one of the rain conditions. This focus reduces the number of species to species selected along such gradient and allow to ignore species that would not be present anyway. This selection does not take into account any competitive mechanisms that could change the identity of the dominant species in a given condition. Nevertheless, information on how the relative performance of theses species can still be collected.

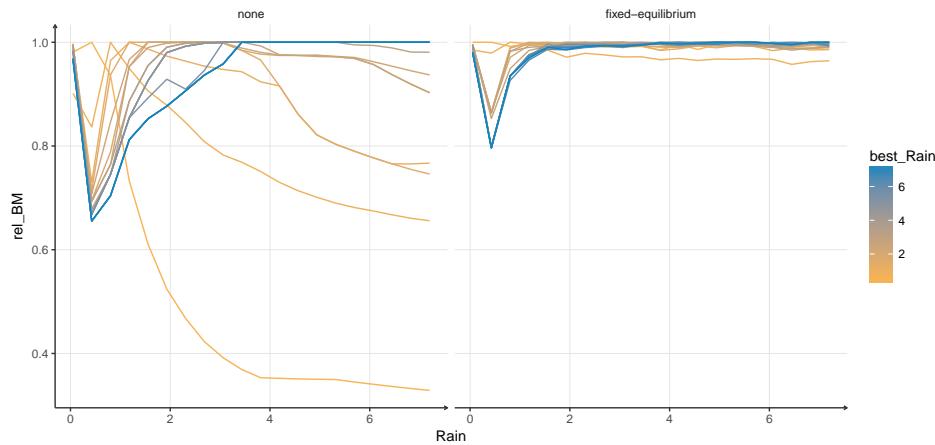


Figure 2.7: Median relative performance of best phenotypes along a precipitation gradient for 20 parameter sets.

2.2.3 Results: gradient of heterogeneous precipitation conditions

Along the temporal heterogeneity (increasing negative slope of water influx) gradient the median biomass of the optimum phenotypes decreases under all allocation algorithms when the variability increases despite the same mean water influx. The amplitude of reduction varies with the allocation mechanism: *non plastic* algorithm shows the largest decrease while *fixed traits* algorithms show slower decrease. *Plastic-optimisation* simulations have more constant performances with low initial performances in constant condition (between 5% and 55% on the *non plastic* simulation), but they end with slightly better performances than *non plastic* simulation for the extreme case of variation (two extreme regimes).

In addition to a reduction of biomass, the increasing slope of the water influx reduction lead to a shift of the optimum strategy in *non plastic* simulations. This reduction of optimum toward more conservative strategies is offset in most of *fixed-equilibrium* and *fixed-optimisation* simulations. A reduction (around 25%) of the 5th and 25th percentiles of the optimum root strategy can be observed between the extreme conditions (constant flux and two distinct regimes) for these two algorithm. This shift in optimum strategy can better be observed on the plan of the proportion of active tissues in root (PAR) and root mass fraction (RMF) in figure 2.8 where all trajectories¹ along the variability gradient are plotted. *Non plastic* allocation trajectories by a linear shift toward more conservative strategies with higher allocation to roots, while *fixed-equilibrium* and *fixed-optimisation* trajectories are non linear and can be divided into two phases: (1) increase in RMF, (2) reduction of PAR. *Plastic-optimisation* algorithm shows no consistent pattern in trajectories.

As previously seen, plasticity can affect diversity in a drastic way, reducing the functional diversity by contracting the phenotypic space, but also increasing the

¹ trajectory of the optimum, not of the species.

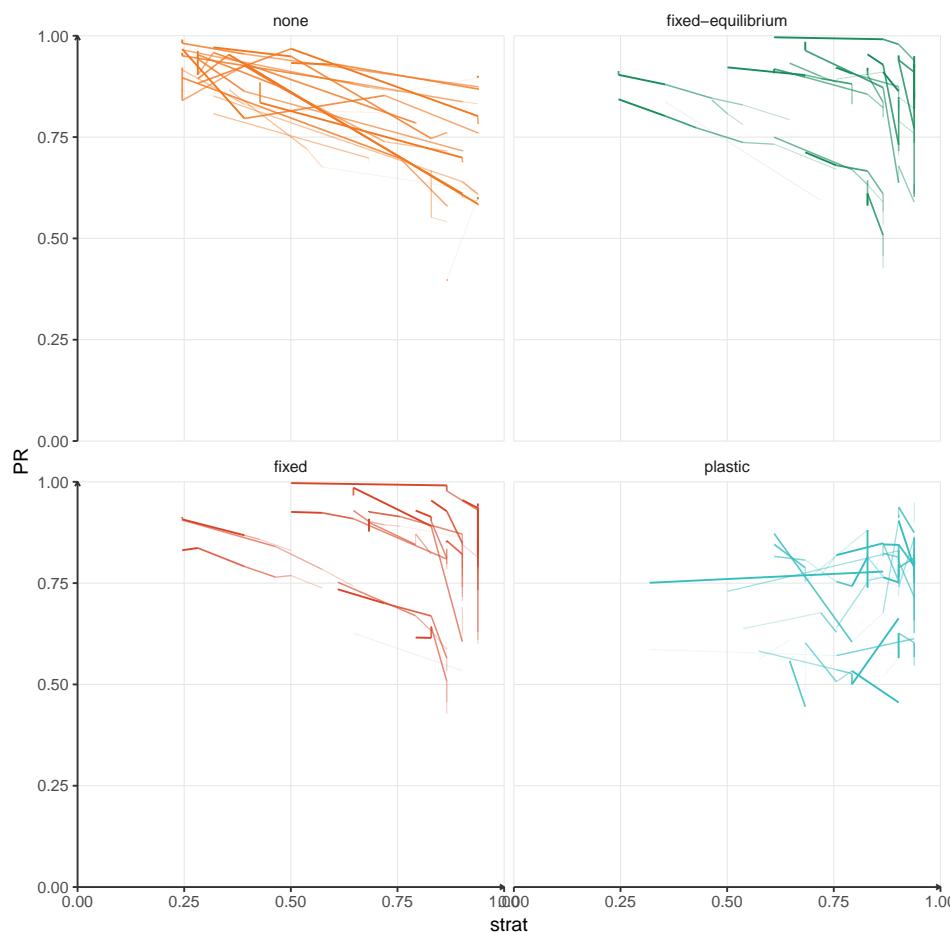


Figure 2.8: Best phenotypes along watering variability gradient. Thinner lighter lines indicate low water variability, while the thicker lines indicate strong temporal heterogeneity.

potential species diversity by the same mechanism. The effect of static gain¹ and dynamic gain must be disentangle. The

Changes in optimum, but does it affect evenness ? Same pattern as before with the trade-off between species and functional diversity. What happen if you filter down stuff ?

¹ refers to the gain due to convergence toward a good static phenotype and no temporal changes.

2.2.4 Discussion: gradient of homogeneous conditions

Along the watering gradient, the optimum strategy (active tissue allocation in roots) changes from conservative toward exploitative. This shift demonstrates that the trade-off between active and structural tissues allocation allows different strategy to dominate in contrasting conditions [1]. This shift occurs for low values of the gradient and exploitative strategies are dominant over a large part of this gradient. This can be explained by high precipitation values disconnected from the precipitation values observed in nature. Also, the low resolution of the strategies (15 values for the proportion of active tissues in roots) limits the possible number of different dominant strategies along such gradient.

Gains from the plasticity can be distinguished between static and dynamic gains. The lower value of the *center of gravity* in conditions of low water availability under *fixed-e*"quilibrium algorithm seems to indicate that conservative strategies benefit from plastic allocation more than exploitative species. However, this effect is mostly due to static gain as the optimum strategy does not change. This effect is due to a growth landscape flatter than in better conditions (more species within the 90-100 % of maximum growth, lower growth difference with best strategy) and asymmetric, that has two effects:

- it reduces the growth gain for species with strategy close to the optimum, but not at the equilibrium (figure ?? panel A);
- increases the potential gain (relative to less flat growth landscape) for species with strategies more conservative than the optimum (figure ?? panel A).

The phenotypic plasticity of the RMF leads to an important widening of the potential niche. This widening is, however, asymmetric because there is a transition of the limitations that define a species niche. Without plasticity, in a given homogeneous environment, the optimum phenotype is defined by both the adequate resource use and its balance. With costless plasticity in RMF, the balance is almost guaranteed and the resource use becomes the main limitation of a species niche. Conservative species are less efficient in high resource availability conditions, while exploitative species are more efficient, but this efficiency decreases quickly as the resource availability does not meet the levels required for these species to maintain high productivity. ... try to expand discussion on this idea.

STRATEGY SHIFT

STATIC AND DYNAMIC GAIN
WHO BENEFIT FROM PLASTICITY

NICHE WIDENING

If costs are low, the effect is likely to reduce potential species diversity. An established species can, thanks to static gain, maintain relatively high growth rate in an habitat where the balance is different but the optimum strategies closed. This is particularly true for rich environment where the optimum strategy for roots is quite stable. The effect on coexistence is better illustrated with an example. Given two species, *species a* and *species b*, with optimum strategy (PAR) and RMF for two distinct conditions, respectively *A* and *B*, in a heterogeneous environment composed of majoritarily condition *A* and minorly condition *B*, ... where do I go with that ? ...

Fitness evenness leads probably to greater competition has there is great overlap of potential niche. However, hard to tell what is the impact on competition and stabilizing effects. Probably negative: so hard to tell effect on coexistence.

FITNESS EVENNESS

Who cares. The ones that are close to the optimum, unless there

WHAT STRATEGIES BENEFIT FROM PLASTICITY?

Mostly static gain, but even if there is gain, increases the potential niche of species that are settled. Bigger niche: favourable for conservative species of rare habitats.

Hard to tell anything on coexistence, except wider niches

2.2.5 Discussion: gradient of temporal variations

Plasticity has a positive effect on exploitative strategies in low resource availability conditions. As said earlier in the document, plant performance depends on multiple things: effectiveness of organs, global resource usage and equilibrium. If plasticity improve the performance of the exploitative species, it is unlikely to be because of the contraction of the space since it is the optimum only that is looked at. Also means it is probably dynamic gain, if the filter was static, plasticity shouldn't have change much. And there is gain, even in the high end of the gradient where the optimum does not move, saying that the optimum is fairly conserved despite increase in resource (but low resolution of the strategy space, and match the function).

IMPROVEMENT IN VARIABLE CONDITIONS

Change in optimum strategy can be explained by: an assymetry in efficiency (better a but more conservative in exploitative favourable conditions than exploitative in conservative favourable conditions) or an assymetry in imbalance cost (better be imbalanced when conservative than when exploitative). The first option is not consistent with previous results (see subsection 2.1, figures ...) that show higher fitness for species more exploitative than the optimum, compared to species more conservative. In the other hand, following results show positive effect of functional equilibrium over conservative strategies. Nevertheless, this effect certainly results from an artefact and the contraction of the phenotypic space not in favour of exploitative strategies. The sensitivity of exploitative strategies to low conditions is visible in figure 2.6

Shift of RMF then strategy explain quite well that the equilibrium is more important than the resource usage and the organ efficiency. How does that inform us on the real world ?

- potentially reduces the meta community diversity if spatial heterogeneity has a less drastic effect on strategic dominance. - talk about that in diversity part /!

may come from a lack of coordination with shoot. Since shoot activity is suppose to be relatively high. == might not have been a good choice to look only at root strategy. But, since there is adjustment of RMF that allow to maintain equilibrium and resource usage, it should be fine to interpret these results.

Phenotypic plasticity give exploitative species an advantage in variable conditions because their growth rate rely more on productivity and therefore equilibrium than conservative species.

The phenotypic plasticity implemented in *MountGrass* improve the relative performance of multiple strategies by concentrating the plant toward a subspace of higher performance for most of plants. Convergence to a smaller subspace can be assimilated to reduction in phenotypic diversity, but it reduce

performance heterogeneity and should favour local plant diversity. However, this effect should be limited by plasticity cost. Indeed, if the growth gain due to plasticity is only static, any species with a fixed phenotype closer to the optimum than the focus species has a better growth rate and exclude the focus species. . a few words on dynamics... Meta-community diversity is however reduced by the reduction of potential axis for niche differentiation. Plasticity costs and limits should play major role in the balance between these mechanisms. Community level simulations are needed to further understand the cumulative role of competition, spatial and temporal variability and plasticity costs on phenotypic plasticity influence on plant community dynamics.

2.3 From model behaviour to competition and coexistence in the real world

2.3.1 Plasticity: new functional diversity

functional diversity of plastic traits? Should them be excluded?

Impact of traits, and abundances: the need to account for it!

May still be useful especially for invasion, and works well despite low flexibility (see [For14]). May allow more diversity if some correlations with other non plastic traits.

2.3.2 Plasticity as a strategy: cost and correlations

and limits ? what about exhaustion

One of the argument to say this is new, however not really explored, neither with plasticity cost perspectives (a bit with plasticity limits) or with tau. However, used extreme cases: give better understanding and necessary before finer analysis. Still, there are hypothesis on the effect on diversity and the role in phenotypic stability (attention: isn't it just because the formulation of projection is wrong that we can make these conclusions ?).

WHO BENEFIT FROM PLASTICITY?
COST OF PLASTICITY
PLASTICITY AS A STRATEGY

2.3.3 Plasticity and competition: changes in interactions

What about the continuous τ gradient ?

EXTENDED INTERPRETATIONS

What about interactions and cycles ? Little has been discussed on the dynamic of the resource and how it could affect coexistence. Imagine that with cycle, reproduction timing has an importance here...

plasticity will change: performance, sensitivity and impact of the resource.

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V

COMMUNITY DYNAMICS

1 COMMUNITY LEVEL SIMULATIONS: NON PLASTIC COMMUNITY

1.1 Parameter filtering

1.1.1 Method

Weather data for the time period between 1959 and 2014 has been computed by the MeteoFrance model SAFRAN by ... using GPS coordinates, slope, azimuth and horizon computed from a digital elevation model. These parameters were also used by the model CROCUS to compute snow accumulation and snow melting. These high frequency data (resolution under 1h) have been averaged on a daily time-step and used to compute input variables for *MountGrass*. The snow in particular defines the length of the growing season starting with the first snow melt of the year and finishing the day of the first snow fall of autumn or winter.

WEATHER DATA

The simulated years above 2014 are randomly sampled from the existing dataset between 1995 and 2014.

Community level parameter filtering is conducted for a new table of parameter sets. These parameter sets are ... from accepted parameters and joined with LHS random sampling for five community level parameters: seed germination density, drought mortality, ageing mortality, plasticity cost for environmental sensing and plasticity cost for trait changes (see chapter 4 for details).

PARAMETER FILTERING

Few words on why plasticity cost parameters: time limits, distinguish the benefit of plasticity itself, not combined effect. Should have done simulations with no cost to have an idea of plasticity cost effect.

The simulations run over 300 hundreds years for 6 sites described in table ?? on squares of ... square centimetres. The simulation is stopped and the parameter set rejected if no individual persist and the seedbank is empty. The seedbank is composed of seeds contained in the seedbank and seeds from the metacommunity. The total of seeds is defined by the seed germination density and the area simulated. The seeds from the simulated community represent up to 80 % of the seedbank, less if the seed production is limiting. The first ... years are not taken into account in the filtering process to let the community settle.

1.1.2 Results

SIMULATIONS

Simulations done. Need to illustrate the results.

On stability and on diversity (functional and species)

EFFECT OF PARAMETERS

Random forest approaches like sensitivity analysis at individual scale.

1.2 Non plastic communities

Trade-off, diversity, stability ...

Is there a selection of some parameters ? Are there ecological trade-off (resource use strategy and reproduction) emerging from the model ? ECOLOGICAL TRADE-OFF ?

2 PLASTICITY: IMPACT ON SPECIES FITNESS AND DIVERSITY

Plasticity in integrated framework and full community simulations. Plasticity mechanisms, but also plasticity as a strategy (look at the cost and tau).

Effects on productivity and coexistence. Difference in the correlation ?

Effect of tau on persistence.

2.1 Plasticity and diversity

Now

2.1.1 Method

To test the effect of plasticity on coexistence and community dynamics, runs from the parameter filtering are used as starting points to limit the simulation time of the stabilisation phase. For each parameter set tested, 6 different sites were tested during the calibration phases, 77 parameter sets were accepted, resulting in 462 communities. Each of those is the starting point of three parallel runs that differ only by the allocation algorithm used: *non plastic*, *fixed-equilibrium* and *plastic-optimisation*. The *fixed-equilibrium* is favoured to *fixed-optimisation* algorithm because previous part of the document focused on this algorithm and because it is simpler to analyse. The *plastic-optimisation* algorithm is still simulated, despite the relatively poor performance results observed in constant conditions and the high convergence, because the introduction of plasticity cost, continuous species specific plasticity ($0 < \tau < 1$), and temporal and spatial heterogeneity should mitigate the negative sides of this allocation mechanism and give information of processes at stake.

SIMULATIONS

2.1.2 Results

Need to run the simulations. Script is almost ready, parameters are filtered from previous step.

Are plastic species more selected than the other ? Probably a bell-shape curves

GENERAL BEHAVIOR
PLASTICITY: A WINNING STRATEGY ?
EFFECT ON COEXISTENCE

VI

SYNTHESIS & OUTLOOK

1 SYNTHESIS

Point out the novelty, achieved work

1.1 Competition and feedback

This document focuses on how the plants are doing with the given resources (arrow in fig in margin). However, a key element in competition and resource dynamics (point that separate Tilman approaches from Chesson) is the impact of plant on resource (fig in margin). Both are fundamental for the understanding on plant interactions, and I argue that understanding the former is necessary to understand the latter and have a global view on plant competitive interactions on resources. blablabla competition experiments, resistance to resource shortening (Tilman) and relative homogeneity of resource (homogeneous in influx, content, starting pool, ... ?). Using the term homogeneous allows to use fixed terms and processes, while to me there is a ambiguity around competition that can be seen as: (1) the impact on growth, (2) the winner out of a competitive scenario (with resource shortening). In this latter case, the approach of part 4 (?) has limited interpretation since they are not competing. We can intuitively imagine (from our understanding of model's functioning) that there is a hierarchical effect on growth, but that is probably reversed in case of (1) shared resource pool (big plant may have access to bigger resource pool in open environment), (2) sufficiently quick resource shortening to lead to death events.

in margin: figure resource and interaction.

figure competition decomposition of fitness (growth and survival), and growth related to resource pool (try to have graph approach).

1.1.1 On plasticity modelling

One strong assumption this modelling relied on was the existence of a strong link between fitness and environmental condition. This has been proven to be partially true as *MountGrass* was able to express improvements in fitness thanks to plasticity. However, in some situations, the plasticity leads to reduction in fitness, or eventually to complete phenotypic dead-end. The temporal dimension of plant growth, and the difficulty to capture that makes this assumption hard to maintain in such complex systems with strong dynamics. Moreover, such assumption do not necessarily take into account competitive behaviours better captured by game theory and other modelling approaches [Far11; Dyb+11].

1.2 The limit of the species.

In this work, but also because of the improvement of molecular biology, and the deeper and deeper dive ecology is doing within individual, the limits of species are fuzzy (started with trait and the introduction of continuity). At some point, there will be a need for a way to go back from the a space of numerous continuous dimensions to the species. Also, understanding species as evolving 3D objects, where the different aspects of intra-specific variations play different shaping roles.

2 OUTLOOK

Further reading, thinking and rambling about what's developed in the papers.

3 EXTENSIONS

THIS SECTION IS MEANT TO INCLUDE THOUGHTS AND IDEAS ON HOW TO EXTEND *MountGrass* BUT THAT COULD NOT BE INCLUDED IN THE FIRST VERSIONS OF THE MODEL FOR VARIOUS REASONS. DESPITE NOT BEING INCLUDED, THESE EXTENSIONS ARE INTERESTING FROM A SCIENTIFIC OR TECHNICAL POINT OF VIEW, AND I HOPE THESE NOTES CAN BE USEFUL TO ANYONE INTERESTED IN *MountGrass* OR INDIVIDUAL BASED VEGETATION MODELLING.

As seen previously in chapter , the emergence of trade-off in growth strategy in the actual framework actually rely on a strong genetic constraint over plant plasticity. Indeed, without plasticity cost and low reactivity there would be a high rate of phenotypic convergence of individuals from different species. This is explained by the existence of optimum carbon partitioning (for a given size) in a stable environment. The coexistence of different resource use strategies (exploitative vs conservative) is allowed only through temporal variations and non equilibrium state. This is quite common since a lot of models will predict rapid dominance of one entity in case of equilibrium (need references here).

Multiple questions arise from this observation: are the conclusions of this work still interesting in the understanding of the coexistence mechanisms? (I hope I did convince you in the dedicated part of this document, see .. for more details), is it possible to see coexistence of multiple strategies in a temporally stable environment? how can we produce trade-off by including only one more resource?

In the following paragraphs I try to answer these questions with theoretical arguments and suggestions on how to integrate them in *MountGrass* .

Coexistence mechanisms are listed and detailed in the introduction of this thesis (see chapter ??). Here I focus on the efficiency of tissues... Nitrogen based, why coexistence ? different phenotype correspond to different limiting resources and for different resource availabilities, different phenotype will optimize the return cost of tissues.Nitrogen also allow the model to have an extra dimension into strategy: WUE (local scale) versus NUE (global scale) (element of reflexion in Maire's thesis).

Its also can be related to

Original idea was to have specific carbon pools for different function, and weight the relative allocation based on gain projections.

3.0.1 Resistance carbon pools

3.1 For more interaction

This model, thanks to paired simulations should be used to explore the effect of plasticity on interactions and competition.

Understanding impact of plasticity on fundamental interaction could nourish the theoretical work on coexistence by linking mechanistic model observations and understanding with more abstract work on the basis of coexistence.

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GLOSSARY

active plasticity Change in phenotype controlled by internal regulation processes. Opposed to passive response. *i.e.* change in SLA when light is limiting is an active plastic response.

allocation rule The allocation rule is the set of rules that determine the target phenotype of a plant considering its actual phenotype, the biomass available and the projection of external conditions. It can be decomposed in two main parts: the plastic dimensions, and the fitness proxy function (or gain function). Allocation rule is also designated as allocation algorithm, plasticity rule or plasticity algorithm.

Plasticity

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