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Matura Paper

Artificial Root Enhancement

A Quantified Approach and Assessment

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Abstract

This paper aims to quantify a concrete approach to enhance the root sizes of plants and subsequently, to assess their possible advantages, threats as well as applications. In order to achieve the firstly presented objective, the phytohormones auxin (IAA) and gibberellin (GA_3) were investigated, the former being generally accepted as the most root growth promoting signalling molecule, while about the latter only very little has been researched in respect to its impact on roots. As for the experimental framework, 72 Arabidopsis Thaliana were treated with five different concentrations, 10^{-3} to 10^{-8} of these biochemicals. By statistical analysis of their root sizes, it could be deduced that at the chosen concentrations neither of the phytohormones could provide an enlargement of the roots when compared to a control group having received solely water, but rather caused an inhibition of growth. Nevertheless, IAA showed a trend of more diluted concentrations inducing the smallest reduction of the root size, thus the one of 10^{-8} M nearly induced a significant increase. This coincides with papers stating that while being promoting in low amounts, IAA acts as a regulator in higher ones. Conversely, for GA_3, no such tendency could be observed in this experiment, despite a similar mechanism being claimed by multiple researchers. Lastly, more sizable roots than naturally common might exhibit the beneficial effects of, for instance, improving the survivability of the plant as a whole or also considerably augmenting the soil quality and durability. Precisely these properties would be most suitable in tackling the issue of desertification mediated by global warming; however, the means of enhancing the roots in the wild remain rather uncertain and controversial.

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1 Introduction

1.1 A Note Regarding Content and Structure of this Paper

Plants are omnipresent in one's everyday life. Not only are they a common sight in either the rural-agglomeration or the city itself, but they also account for a majority of our food intake, amounting to approximately 63% in Switzerland.[1] Therefore, it goes without saying that plants, including their roots, have been profoundly researched. If one further delves into root physiology, one may see that the development, structure and function of this plant part are well understood, on which is going to be elaborated later in this chapter.

However, concerning the applications of root growth enhancing means, the situation appears fairly different. There are indeed many studied possibilities to increase the effective size of roots, namely additional mineral salts, exogenic application of hormones or also genetic modification. Especially regarding the latter, the options seem virtually indefinite. Nevertheless, research must be conducted to concretely describe and quantify procedures so as to be capable of applying them in practice. In case of a planned genetic modification, for instance, it is not particularly helpful if one merely knows the approximate reaction cascade; both the exact sequence in the genome and the best way of its modification must be determined so that the alteration can be executed.

In this sense, I intend to experimentally investigate a specific way of increasing the growth of roots. As phytohormones are the most reliable and appropriate mean for at-home usage, I am going to utilize them to acquire my data, which should identify both the most efficient phytohormone and concentration to be used. Subsequently, the acquired inferences are going to be contrasted with current scientific findings in this field of study. Furthermore, the advantages as well as disadvantages of enlarged roots should be assessed, also leading to a comment on potential applications. Protection against hazards posed by global warming and the role of genetic modifications are themes which may be named in this context. As for the structure, I am firstly going to provide a conspectus of already known, theoretical information about root development along with that of phytohormones. After its introduction, the remaining report of the experiment is going to be presented, followed by its discussion in the light of recent scientific findings and the previously mentioned assessment of such enhanced plants' applications.

[1] Cf. Bundesamt für Statistik (2018), Internet

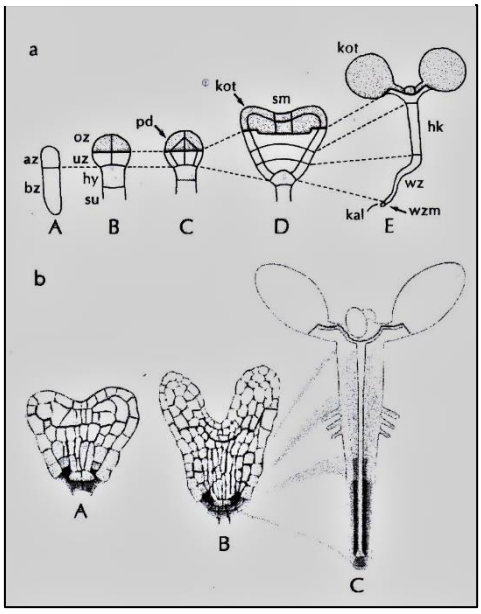
1.2 Root Development and Growth

1.2.1 Embryogenesis

> *"[Roots are] the part of a plant which attaches it to the ground or to a support, typically underground, conveying water and nourishment to the rest of the plant via numerous branches and fibres."*[2]

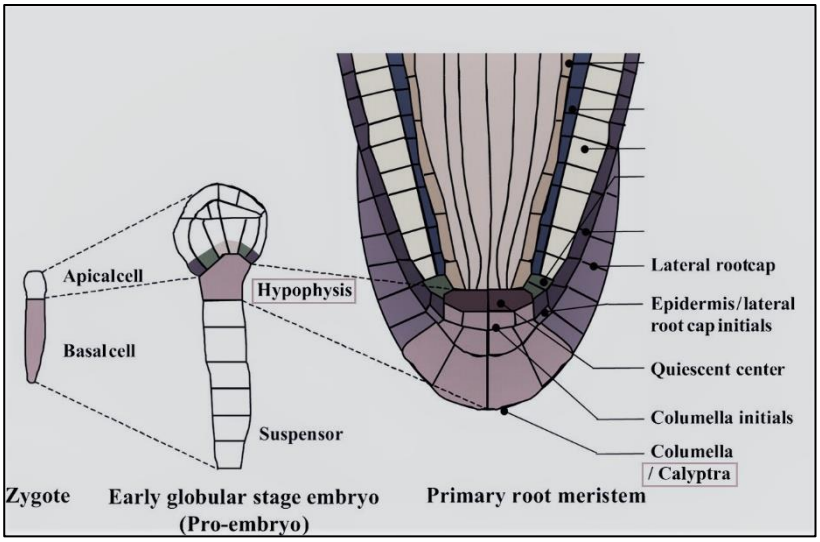
This definition provides a clear image of roots as such; however, it raises the question of how these intricate systems essentially emerge and more importantly regarding this paper, how they increase in size. In order to acquire an answer to the former question, one needs to search as early in a plant's life cycle as the incipient embryonic development; to be precise, in the so-called *heart stage*, termed after the seminal leaves' shape in dicotyledons. It is during this section of its morphogenesis that the developing embryo undergoes the first differentiation which predetermines the future root structure. This may be observed in Figure 1, where the apical cells' basal half divide into three distinct layers. These will subsequently form the lower part of the cotyledonary node, the hypocotyl and the in this case most interesting structure; the *primary root*, also called radicle.[3] At this point it should be noted that two vital segments of the root, the calyptra and the main part of the root meristem, actually derive from the hypophysis, a cell layer helping in connecting the embryo to the endosperm (cf. Figure 2)[4]. In conclusion, this gives a brief insight into the development of the primal state of roots in a seed; nevertheless, they must further grow and proliferate so as to be able to sustain a complete adult plant.[5]

Figure 1: Cell predetermination in Arabidopsis Thaliana: A, zygote. D, heart stage. E, seedling



Source: Schopfer (2010), p. 387

Figure 2: Location and Differentiation of the hypophysis.



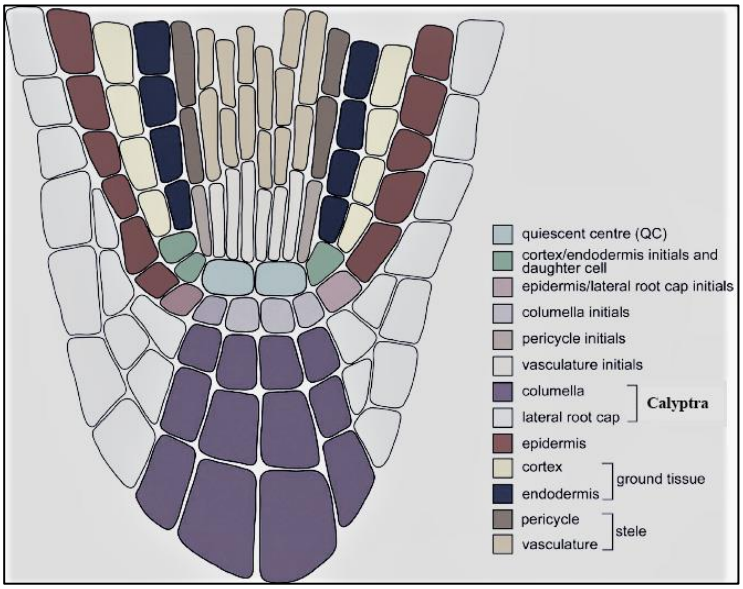
Source: Montiel et al. (2004), Internet (edited text and colours)

[2] Oxford Dictionaries (n.y.), Internet
[3] Cf. Schopfer (2010), p. 384-387
[4] Cf. Goldberg/de Paiva/Yadegari (1994), p. 605-607
[5] Cf. Heslop-Harrison (2017), Internet

1.2.2 The Region of Division

This enlargement is achieved by a growth system unique to plants and relying on the formation of a meristem at the apex, which continuously divides during the plant's life cycle and therefore, supplies the remaining root with additional or renewing cells. For this reason, it is named the *region of cell division* (cf. Figure 3), consisting of a cluster of stem cells as well as loosely differentiated daughter cells. Furthermore, this section is enclosed by the *calyptra*; a protective layer of cells at the roots' tip, shielding the sensitive stem cells, easing movement with mucilage and enabling gravitropism so that the root may grow deeper into the earth.[6] In the midst of the mentioned accumulation of omnipotent cells, or meristem, the *quiescent centre* rests, which is a lenticular layer of cells of varying sizes depending on species and exogenic conditions. The quiescent centre replaces meristem cells in its surrounding, and thus, it might ultimately be described as the stem cells of the stem cells. Furthermore, to execute this function, they are equipped with resistance to unfavourable conditions and due to them having the "lowest rate of DNA synthesis […] and the lowest rates of RNA and protein synthesis"[7], are less prone to genetic mutations.[8]

Figure 3: The region of division and its organisation of stem cells. The amount of cell per structure might very well be higher.



Source: Stahl/Simon (2015), Internet (edited text and colour)

Their omnipotent daughter cells in turn, generally termed initials, generate cells which differentiate to fulfil certain roles. Distally, the stem cells periodically divide in order to replace the cells of the formerly mentioned calyptra; meanwhile, proximal derivatives contribute to the comprehensive growth of the root. They do so by differentiating into specific concentric cell lineages, namely the plerome, periblem and dermatogen, structures on which will be further established subsequently[9] (cf. Figure 3 and Figure 4). What is more regarding root growth, the apical meristem can perform a procedure named *terminal branching*, which is essentially the act of splitting itself and therefore creating a diversion of the main root into one dominant and one thinner derivative.[10] Nevertheless, both of those

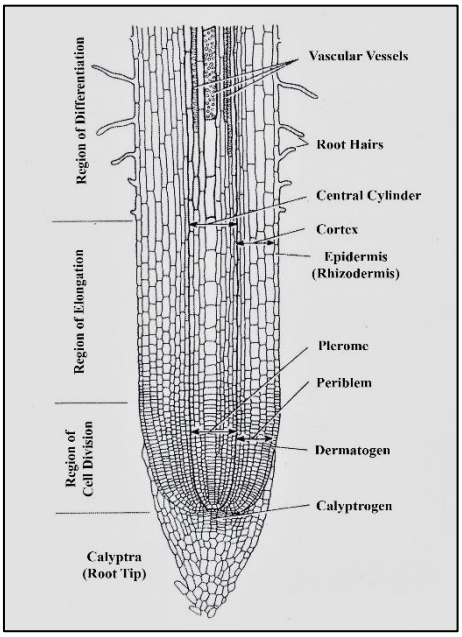
[6] Cf. Iijima, Morita, Barlow (2008), Internet
[7] Kolek/Kozinka (1992), p. 35
[8] Cf. Kolek/Kozinka (1992), p.31-74
[9] Here, a schematic terminology was used; it may vary greatly in different sources (cf. Figure 3) or also regarding the species.
[10] Cf. Gola (2014), Internet

grow by cell divisions, all of which may occur in various directions so as to expand in all dimensions. Despite this omnidirectional proliferation, divisions oriented transversely are considerably more common, one examination suggested 79% of cells followed this direction.[11]

1.2.3 The Region of Elongation

Precisely this is crucial for a root's increase in length, which is likewise important in the organ's second subdivision: the *region of elongation*. Whereas the region of division provided additional cells to the root, in the region of elongation, they undergo extensional growth, which gradually raises the root's total size. This comes at the cost that the cells lose their pluripotency and therefore reduce their frequency of cell cycles. Hence, the meristem continuously distances itself from this region by appending new generations of cells, while leaving those experiencing elongation relatively stationary at their positions. As a consequence, the terminal differentiation of each cell can begin, leading to the next and final segment of the root. However, before, it should be noted that in the region of elongation, plerome, periblem and dermatogen are termed central cylinder, cortex and epidermis respectively.[12]

Figure 4: Schematic illustration of a root's concentric cell lineages and growth regions.



Source: Schopfer (2010), p. 391 (my translation)

1.2.4 The Region of Differentiation

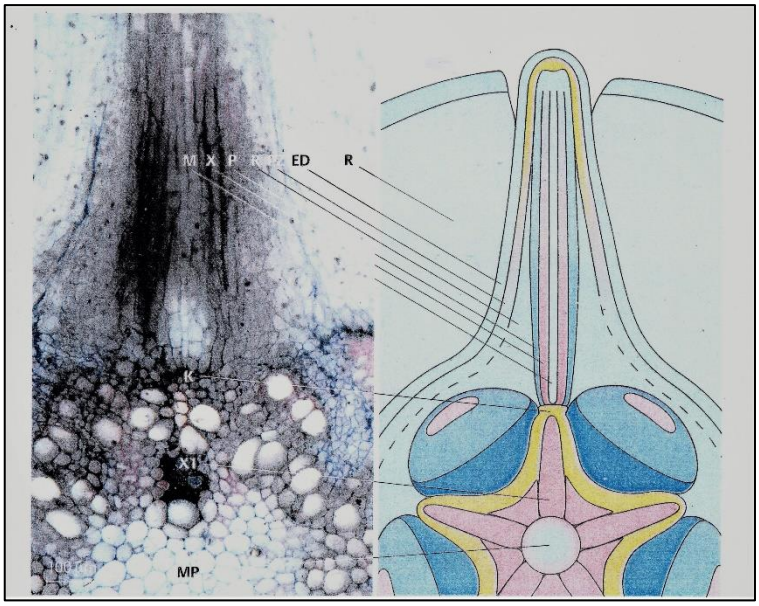
The region of differentiation is the root's last segment, finalising the specification of the cells so that they are capable of performing their assigned function. Its most prominent feature is the formation of minute *root hairs* on the epidermis, or rhizodermis, which greatly enhance the roots' total surface area active in ion- and water-uptake as well as similar processes.[13] However, there are also intrinsic developments, such as the differentiation of the central cylinder into the vascular bundle, consisting of the star-shaped xylem, the phloem and the surrounding pericycle, or that of the cortex' inner periphery into the endodermis.[14] The latter structure is characterized by its suberin-rich Casparian strip, protecting the plant's vessels from detrimental substances by forcing entering water onto the apoplast pathway.[15]

Most interestingly and conversely to the process of differentiation, the pericycle, the outermost sheath around the vascular bundle, possesses the capability of re-embryonising in order to give rise of a new, *lateral root*. Similarly to terminal branching, lateral branching includes the generation of an additional meristem, which then produces its own root cap and continuously extrudes from the inner of the main root with the help of cell divisions (cf. Figure 5)[16]. Over and above, roots might also be formed apart from the main network, at organs such as the stem or leaves. Those are called *adventitious roots* and may either be a result of normal, completely endogenic factors, examples being brace or aerial roots

[11] Cf. Kolek/Kozinka (1992), p. 31-74; Schopfer (2010), p. 387-395
[12] Cf. Shen-Miller/McNitt/Wojciechowski (1978), Internet
[13] Cf. Grierson/Schiefelbein (2002), Internet
[14] Cf. Encyclopaedia Britannica (Ed.) (2018), Internet
[15] Cf. Kolek/Kozinka (1992), p. 53-55
[16] Cf. Péret/Larrieu/Bennet (2009), Internet; Wanner (2004), p. 230-231

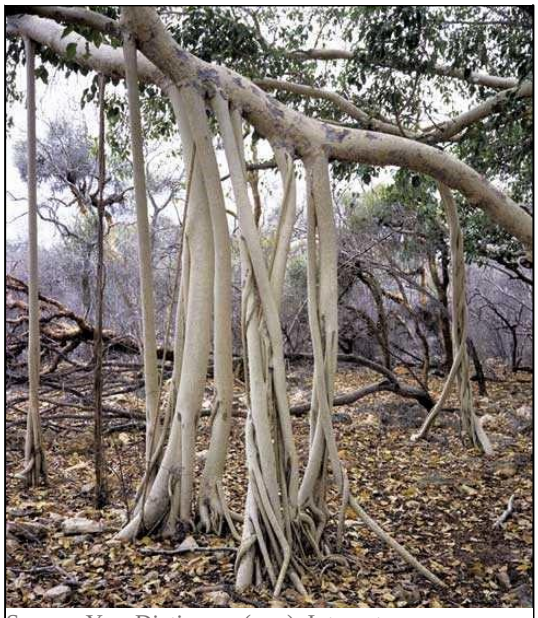
(cf. Figure 6), or that of environmental stress, for instance flooding or partial immersion in soil[17]. Nevertheless, in both cases, they arise in a manner very similar to lateral branching, regulated by phytohormones, which are going to be discussed followingly. Besides this increase in size by branching and primary cell growth, a *secondary thickening* exists in roots, as it does analogously in stems. For simplicity's sake and due to the magnitude of this subtopic, it is merely stated that this development involves the formation of a cambium ring enclosing the vascular cylinder by meristematic cells coming from within it.[18]

Figure 5: Beginning of lateral root formation, where MP marks the centre of the primary root.



Source: Manner (2004), p. 230

Figure 6: Formation of adventitious (/aerial) roots by a tree branch.



Source: YourDictionary (n.y.), Internet

[17] Cf. Steffens/Rasmussen (2015), Internet
[18] Cf. Kolek/Kozinka (1992), p. 75-81

1.3 Phytohormones

1.3.1 An Overview

A plant's life consists of continuous developmental changes, be it of endo- or exogenic cause. On the one hand, the morphogenesis, organogenesis and similar growth processes, which are fundaments for any plant's development, are initiated in response to the entirely intrinsic regulation or promotion of specific genes. On the other hand, there are also developments relying on the production of such molecules in response to completely external stimuli, which include mostly environmental changes or even stress situations. Nevertheless, both of those are absolutely vital for virtually all plants, and are partly, if not entirely controlled by certain signalling molecules: *the phytohormones*.[19]

Phytohormones regulate, as suggested above, a variety of processes by starting signal transduction pathways or acting as a transcription factor itself so as to change the amount of certain substances or enzymes available. This may then have major, visible effects as the flowering during spring, the growth of branches towards the sun (phototropism) or the formation of lateral roots. Furthermore, although they function analogously to human hormones, phytohormones induce reactions mostly in confined spaces, creating a *concentration gradient* along the structure rather than being transported throughout the entire organism. This holds especially true for the hormone discussed firstly, auxin, as it is released mostly in the apical meristems, travelling then down the stem or root respectively, and thus, effectively constitutes different concentrations along that.[20] In spite of the microbiologic and biochemical processes being indeed interesting and fundamentally important, subsequently, mostly the externally prominent consequences of the hormones rather than their exact interactions with various proteins are going to be discussed. Moreover, the text confines itself to those phytohormones fulfilling a fundamental role in root development as well as gibberellin, whereas additional hormones (jasmonates, salicylic acid, systemin and so on) are not going to be further discussed. Additionally, at the end of each subchapter, a brief explanation is presented why that specific hormone is, or is not, going to more thoroughly examined in this paper.

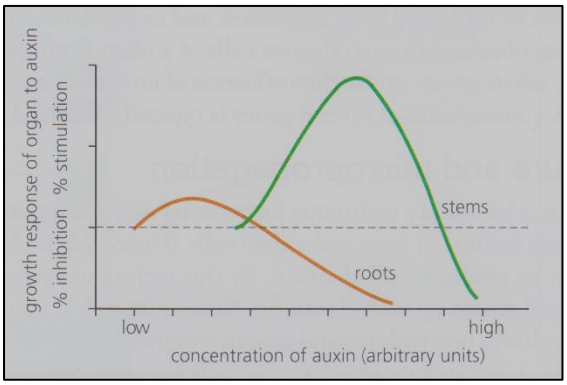
1.3.2 Auxins

The chemical compound commonly referred to as auxin is the naturally occurring indole-3-acetic acid (IAA). Other substances sharing similar effects on a plant's metabolism are mostly artificially synthesized and generally utilized in botanic research. As for the specific impacts, these vary greatly, depending on the affected organ and its *competence*, that is its dispositions to react. The present concentration may also alter a cell's response, which is also substantially supported by the concept of phytohormones often existing in gradients. An example to the former argument consists of IAA having been found to evoke contrary reactions in either stems or roots, depending on the amount available (cf. Figure 7). In general, IAA mediates distinct aspects of overall growth such as the increase of cell elongation or division rate, apical dominance, i.e. restricting the generation of additional shoots, as well as the development of fruit and differentiation of vascular tissues.[21] Again, in roots much dissimilar consequences are observed when compared to the apical dominance; a fast formation of lateral besides

[19] Cf. Wani et al. (2016), Internet
[20] Cf. Galun (2010), p. 227-228; Zhao (2010), Internet
[21] Cf. Ohashi-Ito et al. (2013), Internet; Zhao (2010), Internet

adventitious roots was associated with the hormone.[22] Precisely this along its other qualities rendered IAA particularly appropriate to be investigated in this paper, concerning primarily root growth.

Figure 7: Growth responses of root and stem to different auxin concentrations.

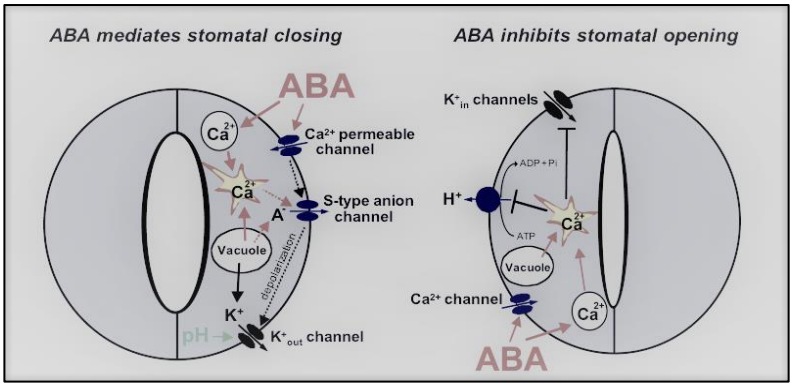


Source: Clegg (2014), p. 399

1.3.3 Abscisic Acid

Despite what the name abscisic acid (ABA) might suggest, it is not involved in the process of abscission; it rather interacts with ethylene, which then induces the corresponding reaction.[23] Nevertheless, ABA's functions are fundamental as well as versatile. On the one hand, those include responses to *stress situations* such as cold and freezing conditions, drought or even pathogenic threats. As an example for the defences against dry environments, the closing of the stomata and thereby reduction of transpiration may be named. ABA achieves this by promoting the outflow of negatively charged and K^+-ions from the plants' guard cells, reducing their turgor and therefore closing the stomata (cf. Figure 8). On the other hand, there are also processes controlled by ABA which include the regulation of seed development as well as internode growth. Furthermore, ABA is also known to show an impact on root growth by increasing lateral root formation along with secondary thickening; however, this occurs mostly in stress situations.[24] Exactly due to this reason, ABA is not further analysed in this paper's experiments, as it would be difficult to contrast the hormones while also creating a water-deficient environment. In addition to that, high ABA concentrations may lead to early death in plants as a result of the stomata being permanently closed, preventing the intake of CO_2 for photosynthesis.

Figure 8: Closing and inhibition of opening in a stoma, induced by an ABA-mediated reaction cascade.



Source: Mäser/Leonhardt/Schroeder (2004), Internet (edited colours)

[22] Cf. Schopfer (2010), p. 413-417, Spektrum.de (1999), Internet
[23] Cf. Galun (2010), p. 151
[24] Cf. IPGSA (n.y.), Internet; Schopfer (2010), p. 426; Tuteja (2007), Internet

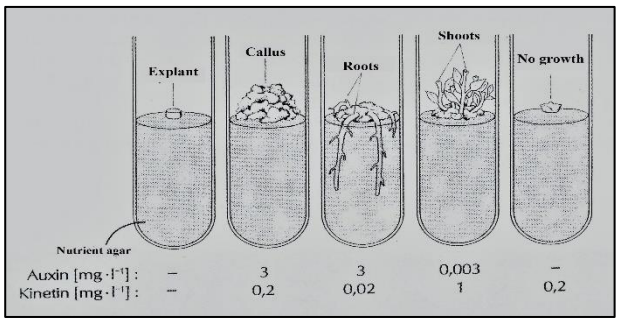
1.3.4 Brassinosteroids

The hormonal group of brassinosteroids (BRs) has been discovered only recently compared to others such as auxins or gibberellins. Nonetheless, this, together with the circumstance of them being found in eminently low concentrations, diminishes by no means their vital roles in healthy plant development. Besides the utter diversity of functions assumed by BRs, such as frost and heat protection, reproductive maturation, various differential processes and many more which cannot be listed here, BRs act mostly as an elongation and cell division promoting agent, similarly to auxins, gibberellins or cytokinins. Furthermore, the ensuing growth is additionally regulated by BRs so that it remains in certain shapes and boundaries. Likewise, this reaction is also evoked in roots, ensuring a correct meristem and root structure by controlling directional division and other factors, which renders these phytohormones most certainly mandatory for sustainable root development.[25] Still, due to the effects of BRs resulting mostly in an overall root size reduction, it is not going to be further investigated.

1.3.5 Cytokinins

Analogously to auxins, cytokinins (CKs), a group of nitrogen-rich adenine-derivatives, are considered one type of the most fundamental *growth enhancing phytohormones*.[26] Hence, their most prominent function comprises as expected the gradual intensification of the mitotic activity of cells and their subsequent differentiation. On the one hand, this affects the number and sizes of shoots, but also leaf structures are altered, i.e. their formation is promoted.[27] Another intriguing impact of CKs is the nearly complete inhibition of leaf senescence, which is in one way achieved by an elevation of chlorophyll levels. Moreover, this explains the idea that CKs are, apart from certain local syntheses, produced in meristematic regions such as the root apex, as this means that those leaves being severed from the main organism decompose due to a lack of needed CK molecules, whereas those still attached receive enough CKs through the vascular bundles so as to remain unimpaired.[28] In general, those findings portray cytokinins certainly as vastly interesting to investigate in regard to their ability to enhance root growth. However, in this paper, another phytohormone was selected to be contrasted against the potency of IAA, which was decided mainly on the basis of an experiment conducted in 1963 by P. M. Ray (cf. Figure 9). It enforced the notion that auxin and cytokinin reciprocally influence the development of the plant and that in this case, CKs would stimulate rather shoot than root growth if present in a considerably higher concentration than IAA.[29]

Figure 9: P. M. Ray, 1963: High dosages of auxin and kinetin on an explant from a Nicotiana Tabacum's pith resulted in the formation of a callus. It could partially be differentiated with the alteration of the hormonal ratio.



Source: Schopfer (2010), p. 425 (my translation)

[25] Cf. Schopfer (2010), p. 432; Tang/Han/Chai (2016), Internet; Wei/Li (2015), Internet
[26] Cf. Barrington (2017), Internet
[27] Cf. Murai (2014), Internet
[28] Cf. Hirose et al. (2007), Internet
[29] Cf. Schopfer (2010), p. 423-425

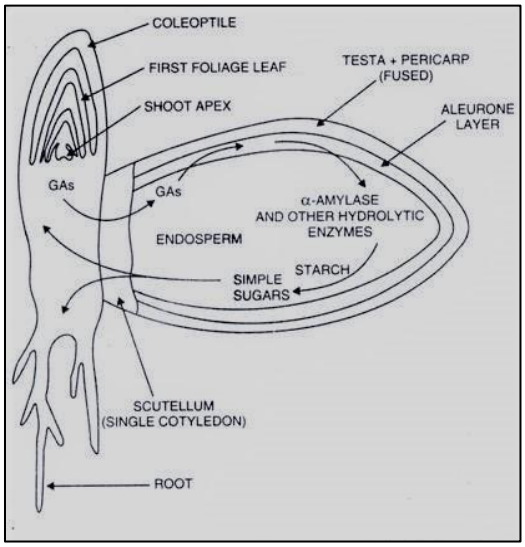
1.3.6 Ethylene

As has been noted previously, the presence of ethylene (ET) gradually increases *ripening* and thus ultimately abscission. For this reason, it has been profoundly studied, and an application of the ET gas was found in the fruit and vegetable industry, where it has become a fundamental part in post-ripening, showing effects like cell softening as well as taste and colour alteration.[30] Similarly, ET influences leaves and flowers, although rather in the sense of stimulating senescence. However, in the year 1970, ET in its solid form ethephon was successfully associated with the feminisation of cucumber plants, which suggests ETs involvement in the determination of vegetal sex.[31] As for the responses of roots to this substance, elevated levels of ET *augment IAA biosynthesis* along with its transportation, resulting in the threshold of IAA's beneficial concentrations (cf. Figure 7) being exceeded in the roots and therefore, inhibiting normal growth and proliferation.[32] Finally, this implies that ethylene would not provide an enhancement of root size and hence is not going to be subject of the following experiments, despite its undeniable necessity in today's food market.

1.3.7 Gibberellins

Shoot elongation is most commonly attributed to gibberellins, consisting of well over 120 distinct molecules, of which the most universal and endogenous ones are gibberellin A1 (GA_1) together with gibberellic acid (GA_3).[33] Due to an induction of *cell wall elasticity*, those chemicals are capable of increasing individual cell growth but also contribute to apical dominance.[34] Additionally, its vital role in plant fertility has been confirmed, namely the correct development of megasporocytes in both stamens and ovaries; however, it was found to provoke flowering itself not imperatively.[35] Besides that, seed dormancy is regulated by GAs, particularly starch hydrolysis in the seed's endosperm, a dead plant part supplying the growing organism with nutrition in the form of large polysaccharide storage (cf. Figure 10).[36] To conclude, especially the firstly mentioned quality of gibberellins (GA_3) intrigued to apply them to roots so as to observe whether they would exhibit reactions similar to those of internodes. It would then be interesting to assess whether its potency in doing so could even surpass that of IAA, as, at the time of making this decision, no adverse effects of GA_3 on the root size were known.

Figure 10: GA promotes the production of starch-decomposing enzymes, augmenting the amount of freely available simple sugar.



Source: Koratkar (n.y.), Internet

[30] Cf. Alexander/Grierson (2002), Internet
[31] Cf. Galun (2010), p. 49-50; Iwahori/Lyons/Smith (1970), Internet
[32] Cf. Iqbal et al. (2017), Internet; Lewis et al. (2011), Internet; Růžička et al. (2007), Internet
[33] Cf. Schopfer (2010), p. 418
[34] Cf. Cosgrove/Sovonick-Dunford (1988), Internet; Suge/Rappaport (1968), Internet
[35] Cf. Gupta/Chakrabarty (2013), Internet
[36] Cf. Schopfer (2010), p. 422

1.4 Introduction to the Experiment

As has been noted, this report concerns the quantification of an approach to effectively improve root growth. For this reason, the potency of the phytohormones auxin (indole-3-acetic acid (IAA)) and gibberellin (gibberellic acid (GA_3)) are assessed with the aim to decide which would offer a larger increase in root size (Experimental Part 1A). Additionally, in a second experimental part (Part 1B) the objective is to be able to identify the most suitable concentration of the added hormone. In order to achieve this, 72 plants are cultivated over a period of two months and under the addition of distinct amounts of the respective hormone. Subsequently, their root volumes are measured, providing the data upon which a conclusion may be drawn. The exact procedure, as well as the related findings, are to be found in the following subchapters. I hypothesize that a 10^{-6} M auxin-solution will cause the largest final root volume. This is on the one hand based on auxin universally being accepted as the phytohormone with the highest capabilities of enhancing root size, as has been noted in the first chapter. On the other hand, the majority of scientific papers, an example may be found in the footnotes[37], declare the molar concentration of 10^{-5} as the most effective one concerning IAA applied on stems and leaves. Hence, according to the theory above, a slightly lower concentration should exhibit an optimum in roots. The corresponding null hypothesis states that there is neither a significant difference between the root volumes of plants treated with distinct hormones nor between those having received different concentrations of the same hormone.

[37] Cf. Karcz et al. (1990), Internet

2 Material and Methods

2.1 Material

This experiment was conducted at home; the used material was thus reduced to more simplified means. For the cultivation of the plants, three identical plastic containers (cf. Figure 11) were employed. They served as a manner of protection and humidity accumulation; furthermore, in each of their bottom segments, 24 culturing media were embedded in order to support a total of 72 seedlings, as shown in the lower part of Figure 12. To raise the mentioned seedlings, approximately 850 seeds of the plant *Arabidopsis Thaliana* were utilized, although retrospectively, a quarter of this amount or even less might have very well been sufficient. In addition to that, different solutions needed to be prepared, which required one gram of each phytohormone, IAA and GA_3, highly concentrated alcohol, here 70% propanol were used, as well as 24 1.5-litre pet bottles. Devices and containers essential to the processes included a small precision balance, measuring three decimal places, together with 25, 100 and 1000 ml measuring cylinders. Further materials which are important for the measuring of the roots are listed after the description of the cultivation process.

Figure 11: One of the used plastic containers.

Source: Own photograph

Figure 12: Top: Soaked nurturing media placed in container. Bottom: Dry nurturing media placed in container

Source: Own Photograph

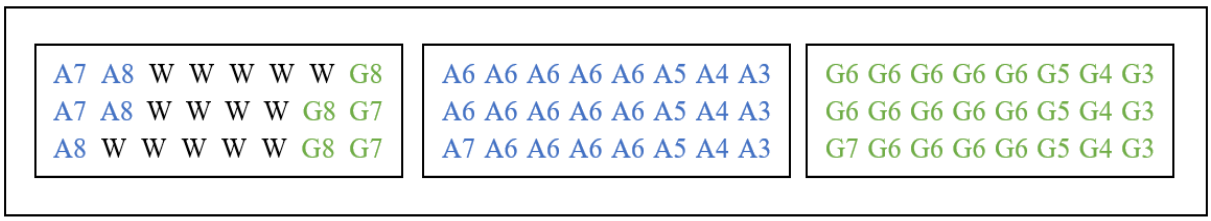
2.2 Organisation and Preparation

Firstly, it was predefined which amount of hormone each solution should hold, and how they will be distributed among the plants. As previously noted, the peak performance of IAA had continuously been determined to lie at 10^{-5} M whereas that of GA_3 had been assessed at roughly 10^{-7}.[38] Therefore, it was reasonable to choose a variety of solutions, ranging from at least 10^{-3} to 10^{-8}. This ensured a broad span of concentrations while not including too high ones, because those, as emphasised before, might inhibit growth in the case of IAA, but also excluding very low concentrations due to those potentially showing no effects in this setup. As for the division of the plants into groups, there should be three large groups and ten smaller ones of the same size. The ones of greater size would provide the data to compare solely the phytohormones with each other. Two groups would receive one of the biochemical each, meanwhile, the third one would serve as the control group being treated merely with water. Both test groups had to be given the same concentration of hormones, namely 10^{-6} M as it was one of the amounts lying in the middle of the spectrum as well as in-between the two concentrations

[38] Cf. Chandler/Robertson (1999), Internet

allegedly causing the most significatn. The groups smaller in size would aid to contrast the different concentrations, which was an additional aim explained previously. In conclusion, the spots for the plants were divided into the following arrangement (cf. Figure 13):

Figure 13: Arrangement of the various groups of plants. W: Plants receiving water. A: Plants receiving IAA. G: Plants receiving GA_3. The numbers represent the negative log of the concentration (e.g. A7 is IAA at 10^{-7} M). Great care was put into having the smallest possible differences in concentration between neighbouring plants.



Source: Own illustration

After the organisational aspects had been finished, the actual preparation of the solutions could follow. For this purpose, 10^{-3} M solutions of each phytohormone were synthesized so as to derive the remaining concentrations by conducting a serial dilution. This initial mixture was composed of one micromole of the respective chemical, 0.175 g in the case of IAA, 0.346 g in that of GA_3, along with one litre of tap water. However, it has to be noted that for the purpose of ensuring a complete mixing of the two substances, both hormones were blended with a small amount of alcohol, 70% propanol in this instance, before their addition to the water. Subsequently, 100 ml of each of the two resulting liquids were given into separate 0.9 litres of tap water, creating 10^{-4} M solutions. Repeating this step four additional times, gave rise to all needed mixtures. These were each filled into separate 1.5 litre bottles, although smaller containers could have very well been chosen. With the intention of surely synthesizing an amount large enough to sustain two months of watering, this complete procedure was executed twice, leading to 1.8 litres of each solution, except for the 10^{-8} M ones as they totalled two litres. During that and future methods, two crucial parts should not be forgotten. Those are on the one side the thorough stirring of the solutions before usage or further processing, and on the other side the explicit labelling of all containers, including those of the plants, with a water-proof pen.

2.3 Cultivation of the Plants

As a first step in sowing the seeds, the culturing media were soaked in water, 25 ml for each to be precise. It was added slowly and carefully, awaiting the complete uptake of the liquid so that no overflowing occurred. Consequently, this process caused the height of the cylindrical soils to increase three- to fourfold, as illustrated by Figure 12, and wet them enough for the seeds to adhere. Approximately ten to fourteen of those were inserted into a groove located in the middle of each medium. This rather high number of seeds was on account of the ambiguity of their success rate; however, as referred to earlier, this number could have indeed been halved due to a later abundance of grown plants. After this initial treatment, they were put in a rather shady place, where the climatic conditions were more or less equal for all containers.

Figure 14: Container number 1 at 19 September 2018, one day before the removal of the unwanted plants.

Source: Own photograph

From this point onwards, daily photos of the plants were taken. Moreover, every third day, each medium was administered 10 ml of its corresponding solution, after the decantation of any remaining water inside the containers. After having followed this procedure 38 days, multiple seedlings had grown in every nurturing pot (cf. Figure 14); however, only one plant would later be measured, and therefore, additional subjects had to be removed from the soil. Those to remain were chosen according to three basic criteria: they were rooted at least 0.5cm apart from the media's edge, had a length as large as possible and were rather isolated from any other plants in order to avoid them being damaged when detaching the redundant ones. The removal was performed as gentle as possible, but nevertheless, the complete root structure was to be taken out.

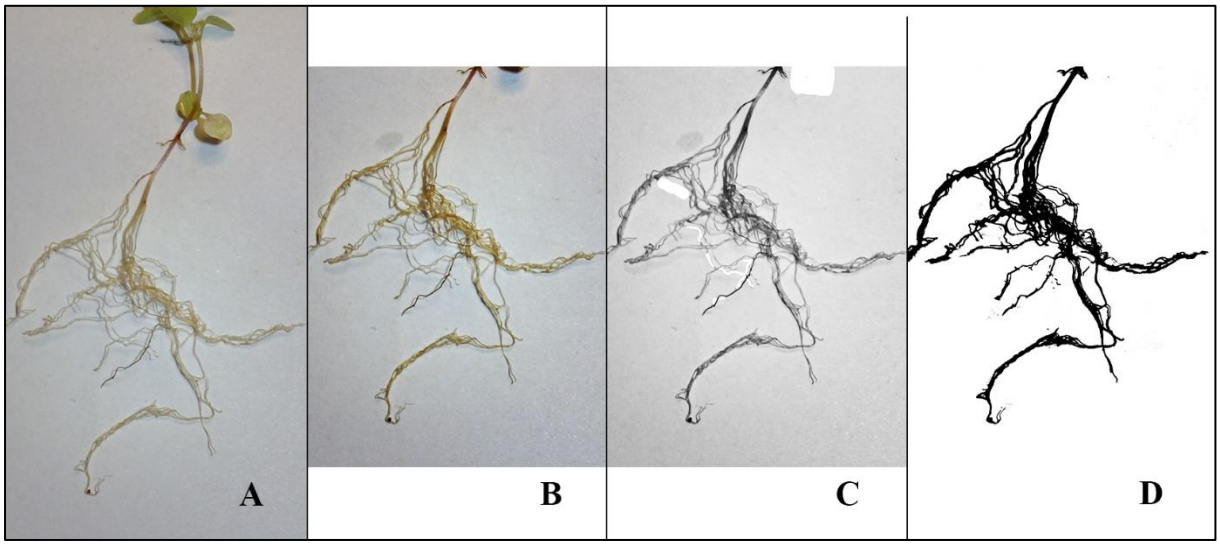
2.4 Measurements

When another 30 days had passed, the measurement of the roots was due. An initial approach was to immerse the plants' roots into a vessel completely filled with water, with the intention of quantifying the amount of displaced water and hence the root's volume. To do so, an eight by eight cm square of blotting paper was cut out, weighed and placed in a flat bowl with a radius of seven cm. On top of it, a glass with radius two cm as well as a height of five cm was positioned and filled to the verge of overflowing. Now the plants were removed from the nutrition media by carefully dismantling areas unconnected to the root system and washing persistent earth particles away, which happened mostly effortless. As a next step, the roots to be gauged were inserted into the water glass, whereupon they would have caused water of their volume to overflow and subsequently be absorbed by the blotting paper. This would have once more been weighed, providing the volume of the soaked-up water by multiplying the difference between the two weights (in kg) with the density of water.

Unfortunately, as the roots were much tinier than expected and thus, did not trigger any spilling in most cases, this procedure could not be conducted. For this reason, an alternative method needed to be chosen, which was the photographic documentation of the plants. It would serve as a mean of quantifying the roots' area by analysing the number of pixels they would occupy in a photograph. Although this was not entirely equal to measuring the volume, the area of roots when spread apart is nevertheless proportional to it as roots are mostly tubular. As preparation for the photographs, every plant was flattened on a white, highly illuminated surface in order to avoid the formation of shadows or overlapping of roots. Afterwards, two pictures were taken, the second of which was shot after a 90° rotation and anew compression of the subject with the intention to account for the possibility of lateral roots protruding from the background and hence being foreshortened. Furthermore, both a constant image size of 5.5 cm and zoom of 6.5X was maintained with the intention of obtaining approximately the

same number of pixels per photograph. Thereafter, each picture was imported into an image editing program; here *Photoshop* was used, overlaying a black-and-white as well as a contrast enhancing filter. This would help in selecting the thus considerably darkened root system with the so-called “magic wand” tool and display the number of pixels entangled by this outline under the tab “histogram”. As this was not always absolutely sufficient for a precise selection of the roots, techniques such as manually lightening the background and adjusting the gradation curve to display more extreme hues had to be applied. One complete example may be observed below in Figure 15.

Figure 15: A: An example of a photographed plant, the one here being the first picture taken of sample 13 of the water control group. B: Firstly, a contrast enhancing filter was applied and the image reduced to the needed root structure (the criteria for the determination of the boundary between root and internode will be elucidated in the chapter “Discussion, Sources for Errors”). C: Subsequently, a black-and-white filter is laid over the picture, and all shadows or other non-root structures are overpainted in white with the help of the “magic wand” tool as it enables the selection of equally, or differently, shaded areas. D: Lastly, the contrast is augmented into the extremes by polarising the gradient curve into absolute black or white, with only little grey in between left. Having done so, the “magic wand” could be employed once more. Due to its complete and even darkness, the entire root structure would thus be added to the selection, whose area could then be determined in the window “histogram”.



Source: Own illustration

3 Results

3.1 Experimental Part 1A: Contrasting IAA and GA_3

3.1.1 Part $1A_1$: Comparison at Standard Concentrations

By comparing the number of pixels each plant's root system is capable of covering, it can be determined which of the two hormones, indole-3-acetic acid or gibberellic acid, shows the most effective root enhancement, or whether neither significantly increase the root size in contrast to pure water. However, the number of pixels as the unit of measurement must first be defined. As has been noted, analysis of each plant was based on two photographs shot with a 6.5X zoom, a resolution of 350dpi and an image height of 5cm (vertical format). Theoretically, the conversion to square millimetres could be performed, for which a formula is presented below (cf. Eq. 1). Nonetheless, the data is kept in its original unit for this results section due to a conversion potentially adding certain assumptions which could not be made to that extent. Additionally, from a personal perspective, to remain as close as possible to the measured figures instead of altering them appears to be the most sensible approach.

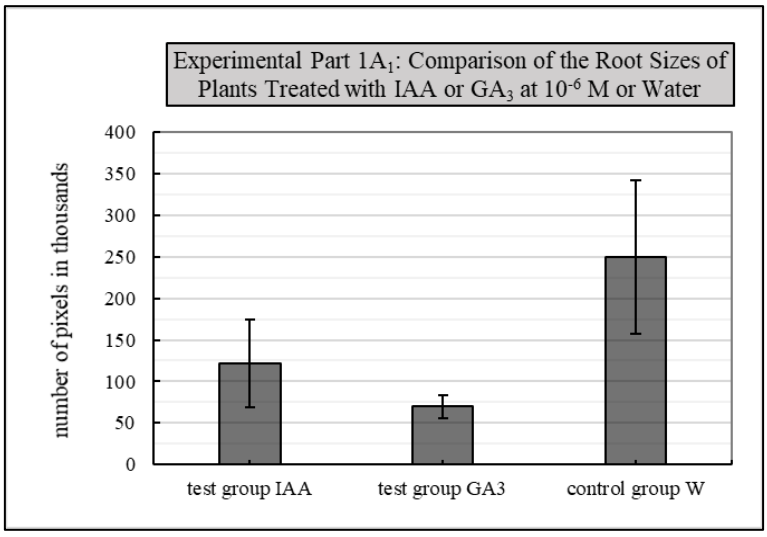
$$A = \left(\frac{25.4}{r}\right)^2 \times n$$

Equation 1: Conversion of number of pixels into area in mm^2
A = area in mm^2
r = resolution in dpi
n = number of pixels

Source: Own Equation

As for the statistical analysis of the two hormones' potency, in a first step, the root areas of the 14 plants grown with a 10^{-6} M solution of either IAA or GA_3 are compared with those of subjects which received pure water. This serves as a standard concentration to contrast the hormones independently from their amount given. To do so, the raw data, which may be viewed in the appendix, is condensed to a table and graph indicating the arithmetic mean value and standard deviation, in order to present these results in a summarised manner (cf. Figure 16 and Table 1).

Figure 16: Graphical presentation of the means and standards deviations of the groups IAA 10^{-6} M, GA3 10^{-6} M and water.



Source: Own illustration

Table 1: Means and standard deviations of the groups IAA 10^{-6} M, GA_3 10^{-6} M and water.

Experimental Part $1A_1$: Root Sizes in Pixels		
IAA (10^{-6} M)	GA_3 (10^{-6} M)	Water
Ø = 121284 ± 52785	Ø = 69972 ± 13912	Ø = 250177 ± 92448

Source: Own illustration

As may be observed in this table and diagram, pure water ultimately caused the largest final root size, with IAA coming second. However, this finding's *statistical significance* must be verified prior to accepting this as a fact. On a first glance, the mean values seem to display a considerable difference, but the error indicators ought not to be forgotten as those each interleave with at least one other group. In order to objectively examine the significance of this data, an unpaired *Student's t-test*, whose equation is found below (cf. Eq. 2), is executed. Intermediate results may be found in the appendix.

$$t = \frac{(\sum D)/N}{\sqrt{\frac{\sum D^2 - \frac{(\sum D)^2}{N}}{(N-1)(N)}}}$$

Equation 2: Formula for Student's t-test
t = t-value, indicator of significance
$\sum$D = differences of group 1 and 2 at each sample number summed
$\sum D^2$ = squares of each difference summed
N = total number of samples

Source: Statisticshowto1 (n.y.), Internet

Having calculated the *t*-values of the differences between all groups (cf. Table 2), those need to be compared to the corresponding *p*-value, a number which must be surpassed for the *t*-value to be considered significant. The p-value varies depending on the α-level, also called significance level, which is a percentage representing the probability of the two groups' data differing in this way simply by chance, not because of the different conditions in each group. In this experiment, it is chosen at 0.05 due to this being common practice in most scientific papers. By consulting the table of Student's *t*-distribution[39] and setting the degrees of freedom at 13, due to *n* being 14, as well as the mentioned α-level at two-sided 0.05, one receives the *p*-value of 2.160. If now the calculated values are contrasted with this one, it becomes apparent that the data, and thereby the root sizes, differ significantly under these criteria; however, the *t*-values are not utterly larger than the minimum threshold of significance, especially if the discrepancy between the test group IAA and the control group is regarded. Nevertheless, on the basis of this statistical test, the null hypothesis can be rejected and the alternative hypothesis of there being a significant difference accepted.
Hence, this experiment indicated a considerably different growth when plants are watered with IAA or GA_3 instead of water but also when comparing the tow hormones themselves. Unfortunately, in regard to the

Table 2: T-values gathered with Student's t-test for differences between the two test groups and the control group as well as the corresponding p-value

Part $1A_1$: *t*-values (rounded to four DP)	IAA (10^{-6}) - Water	(-) 2.1888
	GA3 (10^{-6}) - Water	(-) 2.4076
	IAA (10^{-6}) - GA_3 (10^{-6})	3.2089
	Minimum value (*p*-level)	**2.160**

Source: Own illustration

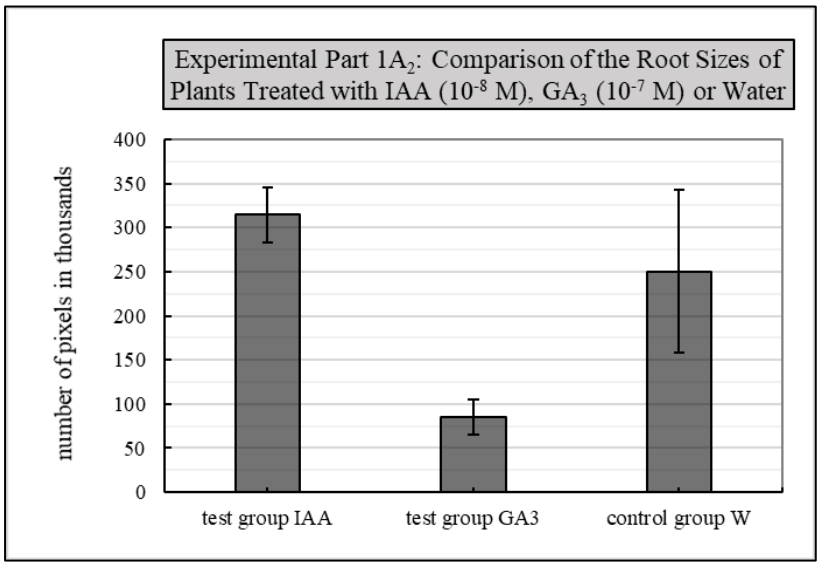
[39] Cf. Sjsu.edu (2007), Internet

postulated hypothesis, the hormones caused a decrease in root size.[40]

3.1.2 Part 1A$_2$: Comparison at the Most Effective Concentrations

For a concluded comparison and therefore alternatively to a rather arbitrarily chosen standard concentration, the most potent amounts of each hormone should also be considered in the analysis. This stems from the possibility of 10^{-6} M being a very inefficient concentration for either phytohormone and thus presenting that as less influential as it may be. The identification of those two concentrations is treated thoroughly below; nonetheless, they are contrasted already at this point. For IAA, 10^{-8} M appears to have caused the highest increase in root size, whereas 10^{-7} M demonstrated the best result for GA_3. For these sets of data, the initial approach remains identical to previously, and for this reason, solely figures and tables are presented (cf. Figure 17, Table 3 and Table 4).

Figure 17: Graphical presentation of the means and standard deviations of the groups IAA 10^{-8} M, GA3 10^{-7} M and water.



Source: Own illustration

Table 4: Means and standard deviations of the groups IAA 10^{-8} M, GA3 10^{-7} M and water.

Experimental Part 1A$_2$: Root Sizes in Pixels		
IAA (10^{-8} M)	GA_3 (10^{-7} M)	Water

Table 3: T-values gathered with Welch's t-test for differences between the two test groups most efficient concentrations and the control group as well as the corresponding p-values and estimated degrees of freedom (DFs).

Experimental Part 1A$_2$: Figures Necessary for the Statistical Analysis			
	v (estimated DF)	*t*-value	***p*-level**
IAA (10^{-8}) - Water	10,677	2,108	**2.228**
GA_3 (10^{-7}) - Water	14,741	(-) 6,074	**2.145**
IAA (10^{-8}) – GA_3 (10^{-7})	3,389	10,722	**3.182**

Source: Own illustration

[40] Cf. Statisticshowto1 (n.y.), Internet

Evidently, Table 4 is much more extensive than the former equivalent. This is a result of the two test groups being of another size than the control group, and thus, the student's *t*-test could not be applied anymore. As an alternative, *Welch's t-test* was chosen, which is generally used when different variances or sample sizes are present. Its calculation is rather simple and found below (cf. Eq. 3); however, as *N* is not the same when comparing the control group with any of the two test groups, the degrees of freedom cannot be easily determined. For this matter, a second formula, the *Welch-Satterthwaite equation* (cf. Eq. 4), must be employed, providing an estimation of the degrees of freedom for each difference between two groups, which is then conservatively rounded down to the next integer. In turn, this presented for all three comparisons individual *p*-levels, likewise acquired from the table of Student's *t*-distribution[38]; once more in the column of 0.05 as well as two-sided. While the other comparisons revealed an absolutely significant difference, that of the plants given IAA and those having received water does not surpass the minimum value connected to its estimated degrees of freedom. This means that in Table 4's lower two cases, the null hypothesis can successfully be rejected, implying that with a confidence of 95%, it may be said that GA_3 at 10^{-7} M caused the Arabidopsis to grow significantly smaller roots. In contrast, concerning the test group IAA and the control group, the null hypothesis cannot be eliminated and thus, it must be assumed that there is no statistically significant difference in plants' root area cultivated with either the help of a 10^{-8} IAA solution or merely tab water.[41]

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{{s_1}^2}{N_1} + \frac{{s_2}^2}{N_2}}}$$

Equation 3: Formula for Welch's t-test
t = t-value
$\overline{X}$ = arithmetic mean
s = standard deviation
N = number of samples
$_1$ or $_2$ = indication whether the value of group 1 or 2 is inserted

Source: Statisticshowto2 (n.y.), Internet

$$\nu \approx \frac{\left(\frac{{s_1}^2}{N_1} + \frac{{s_2}^2}{N_2}\right)^2}{\frac{{s_1}^4}{{N_1}^2 \nu_1} + \frac{{s_2}^4}{{N_2}^2 \nu_2}}$$

Equation 4: Welch-Satterthwaite equation
ν = estimated degrees of freedom
ν_1 or ν_2 = degrees of freedom of group 1 or 2 respectively
s = standard deviation
N = number of samples
$_1$ or $_2$ = indication whether the value of group 1 or 2 is taken

Source: Wikipedia (n.y.), Internet

3.2 Experimental Part 1B: Identifying the Most Efficient Concentration for Each Phytohormone

In this shorter section, the most suitable concentration opposed to hormone should be ascertained. With that intention, a table and corresponding diagram were prepared (Table 5 and Figure 18), displaying the two hormones' mean root size at a given concentration as well as its error indicators. The values for the control group were inserted for the sake of completeness and perspective as it indicates which concentrations possess the possibility of inducing greater root growth.

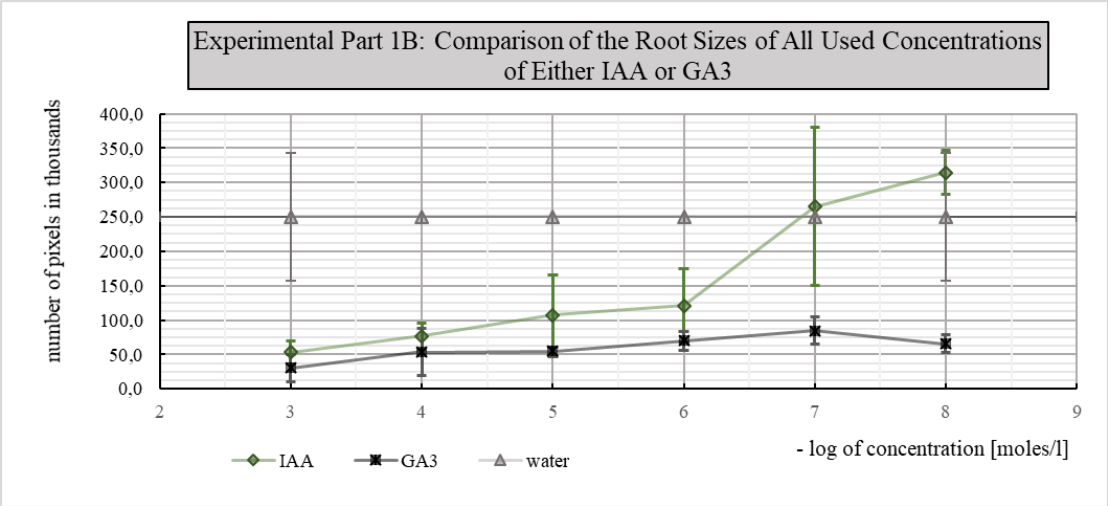
[41] Cf. Statisticshowto2 (n.y.), Internet; Wikipedia (2018), Internet

Table 5: Means and standard deviations of all measured groups.

Experimental Part 1B: Comparison of the average root sizes of all used concentrations of either IAA or GA_3			
Concentration	**IAA**	**GA_3**	**Water**
10^{-3}	53417 ± 16659	30225 ± 19819	250177 ± 92448
10^{-4}	76564 ± 18649	53703 ± 33718	250177 ± 92448
10^{-5}	107002 ± 58645	54188 ± 7014	250177 ± 92448
10^{-6}	121284 ± 52785	69972 ± 13912	250177 ± 92448
10^{-7}	265247 ± 115128	84623 ± 19938	250177 ± 92448
10^{-8}	314763 ± 31377	65711 ± 13119	250177 ± 92448

Source: Own illustration

Figure 18: Graphical representation of the means and standard deviations of all measured groups.



Source: Own illustration

By reference to this diagram, one is able to infer that merely 10^{-7} and 10^{-8} molar IAA has the potential of providing named enhancement of root size, whereas higher concentrations of IAA, or GA_3 in any amount, hampered the development when compared to plants having received only water. Now, when turning to the statistical significance, it has already been established that the group IAA 10^{-8} M as the apparently most potent one did not provide a significantly larger root size, which may very well also be adopted for the concentration 10^{-7} due to the water group being wholly immersed in its standard deviation. On the other hand, GA_3 at 10^{-7} has proven to considerably, that is significantly, reduce the root size, which in this instance may be assumed for all remaining concentrations of this hormone as they show even smaller means in addition to standard deviations, with the exception of 10^{-4}. Having considered all these aspects, no concentration of either hormone could be verified to be more efficient than the control group; however, the group 10^{-8} IAA was at the verge of significance, so close in fact that if the estimated degrees of freedom had been rounded arithmetically, the *p*-level would have been exceeded. Thus, a tendency may nevertheless be noted. As for the remaining sets of data, the comparison of each possible combination of concentration and phytohormone with the help of the Student's *t*-test is renounced due to it adding unnecessary volume to this chapter without contributing considerably

to the research question. Nonetheless, the *correlation* between the change in amount and alteration of root size for both substances is tested so as to be able to provide a conclusive statement concerning the reliability of the measurements.

$$R^2 = \frac{N(\sum xy) - (\sum x)(\sum y)}{\sqrt{[N(\sum x^2) - (\sum x)^2][N(\sum y^2) - (\sum y)^2]}}$$

Equation 5: Formula for R^2-value, indication of correlation between x- and y-axis
R2 = coefficient of correlation
$\sum x$ = sum of x-values (here -log of concentration)
$\sum y$ = sum of y-values (here root size of either IAA or GA_3)
$\sum x^2$ = squares of each x-value summed
$\sum y^2$ = squares of each y-value summed
N = number of samples

Source: TutorVista (n.y.), Internet

The above equation (Eq. 4) was applied, which provides the R^2-value; a number seeking to indicate the ratio of the variance explained by the change in the x-axis to the total variance. For *x* the negative logarithm of the concentration and for *y* the related root size in pixels was used. However, it needs to be noted that no mean root size was inserted but rather, when taking 10^{-4} IAA as an example, the number four was written three times in the column for ***x*** while in the column *y* the figures 97136, 71790 and 60765 were inserted. The exact tables may be viewed in the appendix. Finally, the R^2-values can be analysed, giving an approximate correlation of 72% for IAA and 63% for GA_3. These values depict the data as rather unreliable when viewed in light of the common standard of 95% as a minimum threshold in scientific studies.[42]

3.3 Additional Observations

Not only did the phytohormones affect the plants' roots, but they also changed the remaining appearance considerably. GA_3, for instance, caused a general elongation and whitening of the internode, rendering the plants rather fragile and unable to independently remain upright, which lead to them intertwining much more often. This characteristic, together with a reduction in leaf size, was especially prominent among subjects having received concentrations of 10^{-6} M and higher, seemingly preventing healthy development. On the opposite, the IAA control group expressed equal to slightly shortened internodes in contrast to the control group; as well as formed fewer leaves, which was also particularly pronounced with higher concentrations. In Figure 19, Figure 20 and Figure 21, the plants' properties may be examined, although it must be said that some organisms of the individual groups were more dried out than others due to them being removed from their soil and photographed earlier.

[42] TutorVista (n.y.), Internet

Figure 19: All 29 plants treated with IAA. Concentrations are arranged in groups of three, or 14 in the case the fourth one, starting left at 10^{-3} M, ascending to 10^{-8} M at the very right.

Source: Own illustration photograph

Figure 20: All 29 plants treated with GA_3. Concentrations are arranged in groups of three, or 14 in the case the fourth one, starting left at 10^{-3} M, ascending to 10^{-8} M at the very right.

Source: Own photograph

Figure 21: All 14 plants treated with water.

Source: Own photograph

4 Discussion

4.1 Analysis of Results Relating to IAA

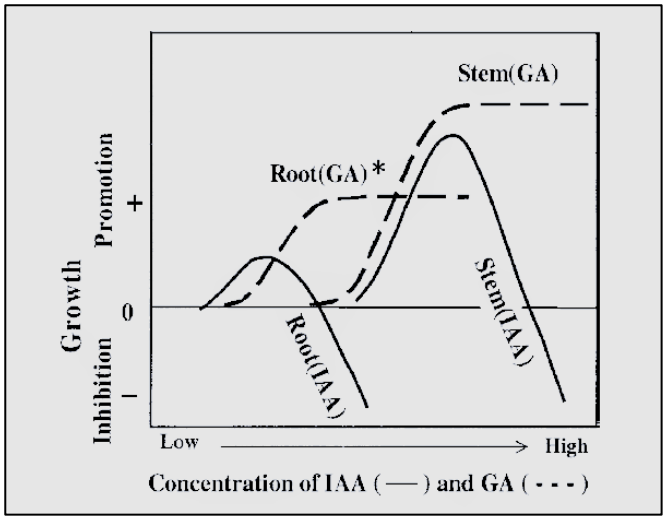
4.1.1 Inference

Firstly, the results regarding the addition of differently concentrated IAA solutions are analysed. As has been noted in the corresponding results section, none of the concentrations from 10^{-3} to 10^{-8} M could provide a statistically significant increase in root size when compared to the control group having received water. However, the plants of the 10^{-8} M group were very close to being recognised as possessing larger roots, especially if a less conservative approach had been chosen. Meanwhile higher concentrations, those ranging from 10^{-3} to approximately 10^{-6} to be specific, caused surprisingly a significant decrease in the plants' root sizes. Therefore, a trend towards 10^{-9} M and lower concentrations may be described as more beneficial for root growth.

4.1.2 Auxin Can Enhance Mitotic Activity, Elongation and Lateral Root Formation

Both those changes may be described with the initially provided information about IAA and its effects of increasing root growth and lateral root formation at certain concentrations (cf. Figure 22). Again, the exact biochemical processes and interactions are enormously complex, relying on an abundance of auxin-responsive transcription factors (ARF), AUX repressors, their IAA-mediated ubiquitination (specified peptide degradation), which act on auxin-responsive genes (ARGs) and are again themselves controlled by eclectically regulated gene expressions. In both this and the following subchapter an attempt is made to outline the principal structures of these molecular interactions, despite only touching upon the comprehensive knowledge which has been acquired through research in this field.[43]

Figure 22: Promotion or inhibition depending on the affected organ and the concentrations of IAA or GA_3



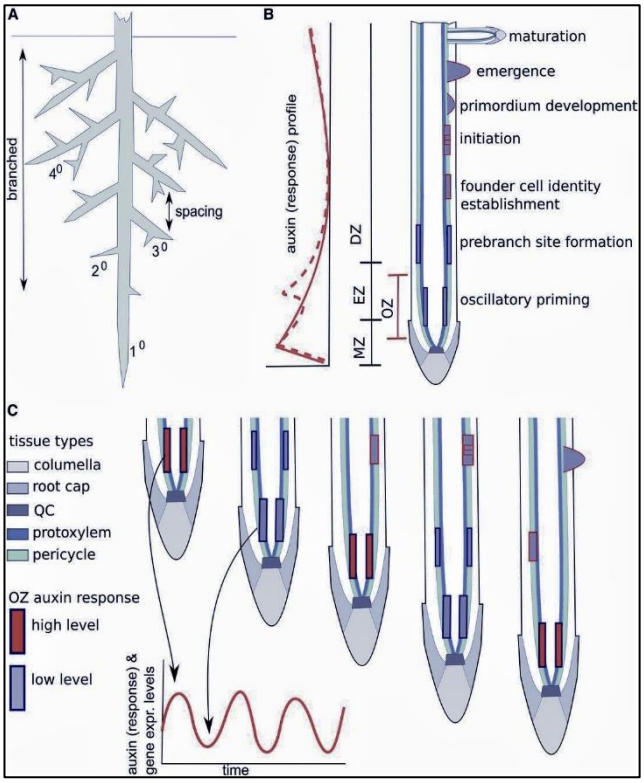
Source: Tanimoto (2015), p. 251 (colours edited)

[43] Cf. Galun (2010), p. 40-48; Petersson et al. (2009), Internet

In an untreated root, *distinct auxin concentrations* are vital for its development. Both the locally produced auxin and that transported through the phloem from the shoot's meristem by polar auxin transport (PAT) establish an auxin maximum in the root tip, or quiescent centre to be exact. This high occurrence promotes auxin-dependent genes such as the *PLETHORA*, *SCR* and *SHR* genes, which are essential for the *pluripotency* of the root meristem and stimulate cell division. Yet, those more rapid divisions, beyond other reactions to high auxin concentrations, reduce the elongation of those cells. In sections further away from this maximum, these stem cell abilities are lost but in return, the elongation mentioned is not inhibited anymore. Mostly it is even promoted by IAA as it *loosens cell walls* by enhancing the production of biochemicals remodelling them, for instance expansins, and reducing the apoplastic pH-value, inducing so-called acid growth. By activating H^+-ATPases, auxin is capable of hyperpolarising the plasma membrane, resulting in the opening of potassium channels, which subsequently facilitates the inflow of these ions. This enhances the cell's turgor and thus stimulates its growth, although this process is rather limited to younger cells. [44]

However, regarding those cells having left the region of division, increasing the auxin levels there does not necessarily restore their pluripotency due to their limited *competence*, that is to say capacity of reaction, caused by varying availability of Aux/IAA proteins and ARFs. Those are able of either activating or repressing auxin-mediated genes or also the transcription of each other. In short, other proteins present in a cell additionally regulate its response to incoming auxin. Nevertheless, a re-embryonisation is still possible in cells close to the meristem such as those at the boundary between the region of division and that of elongation. "Pulses of auxin signaling"[45] occur regularly along the primary roots protoxylem, which then predestine alternating in sides pericycle cells close to this peak in auxin concentration to initiate a lateral root later. It is also referred to as *priming* and comprises the induction of a genetic alteration in the affected cells, providing them with the capability of perceiving a future signal. This happens when they have reached the region of differentiation, as then high enough levels of auxin sent by the stem apex may reach the prepositioned site, the *primordium*, and inducing the initiation of a lateral root bud (cf. Figure 23). In *Arabidopsis Thaliana*, both the meristematic and basipetal signals were found to occur in intervals of roughly 15 hours. [46]

Figure 23: Illustration of periodic auxin signalling along the primary root. At alternating sides, pericycle cells are primed to later respond to a basipetal flow not shown here.



Source: Laskowski/ten Tusscher (2017), Internet (colours edited)

[44] Cf. Galun (2010), p. 40-48; Majda/Robert (2018), p. 7; Overvoorde/Fukaki/Beeckman (2010), Internet; Pacheco-Villalobos et al. (2016), Internet
[45] Overvoorde/Fukaki/Beeckman (2010), Internet
[46] Cf. Galun (2010), p. 40-48; De Smet et al. (2007), Internet

The formation and growth of this initiation site occur on the one hand due to auxin positively regulating genes transcribing *cyclins or cyclin-dependant kinases*, which are biochemicals most fundamental in the control of cell cycles and thus, increasing their availability, heavily accelerates the rate of division. On the other hand, the *LAX3* gene in the cortex and epidermis cell layers coating this predetermined region, the primordium, is up-regulated. It encodes for an additional auxin transporter which increases the hormone's inflow, and therefore, it creates a "positive feedback loop"[47] by then also promoting the *LAX3* gene in neighbouring cells. In conclusion, auxin has the potential of enhancing both cell division and elongation as well as the number of lateral roots. Thus, exogenous application of IAA may lead to an overall increase both in size and number of roots; however, too high concentrations of IAA result in the exact opposite, which has still to be explained in this paper.[48]

4.1.3 The Auxin-Mediated Inhibition of Root Growth Relies on Ethylene Biosynthesis

One well-founded proposition for this inhibition of root growth at too high IAA concentrations is that it induces the synthesis of the regulatory ethylene gas, which should reduce cell elongation and to some degree meristematic activity.[49] Although there have been studies opposing this notion and declaring ethylene as playing merely a small or even no role in auxin-mediated inhibition[50], multiple sets of data support the former suggestion that auxin in combination with ACC (an ethylene precursor) reduces the growth of roots.[51] One such study published at the University of Extremadura, Spain, claimed that under auxin-induced ethylene production, inhibited epidermal elongation and reduced cell divisions accounted for approximately 88 and 12% of overall root shortening respectively. Ultimately, ethylene gives rise to this regulatory effect by further increasing the auxin concentration inside the outer region of division as well as that of elongation, where this hormone then prevents the natural growth in length.[52] This is achieved by ethylene on the one side by promoting and directing auxin transport primarily to the named regions by for example activating the additional production of PIN1 and PIN7, which are common auxin transport proteins. On the other side, ethylene could positively be linked with the stimulation of IAA biosynthesis by upregulating genes associated with IAA production such as *ASA1* and *ASB1* in the root apex.[53]

As for the exact reason why auxin itself inhibits cell elongation, unfortunately, no precise and reliable information could be found. Solely the process of auxin increasing its own concentration with the help of ethylene and the fact that G-phases of the cell cycle being shorter when auxin promotes the mitotic activity can be provided. It must be assumed that additional causes for its diametrically different effects are based on changing interactions with Aux/IAA proteins and ARFs, reversing its initial effects on genes coding for expansins and other elongation-supporting substances. Besides that, ethylene itself was found to counteract elongation by deranging the microfibrils found in cell walls; however, this is going to be further discussed in combination with GA-mediated responses (cf. Figure 24).[54]

[47] Overvoorde/Fukaki/Beeckman (2010), Internet
[48] Cf. Himanen et al. (2002), Internet; Overvoorde/Fukaki/Beeckman (2010), Internet
[49] Cf. Chadwick/Burg (1966), Internet
[50] Cf. Andreae et al. (1968), Internet; Eliasson/Bertell/Bolander (1989), Internet
[51] Cf. Alarcón/Lloret/Salguero (2014), Internet; Ponce et al. (2005), Internet
[52] Cf. Růžička et al. (2007), Internet
[53] Cf. Swarup et al. (2007), Internet
[54] Cf. SlideServe (2012), slide 17

4.1.4 Concluding Explanation

Considering this rather extensive compilation of IAA's impacts on roots, for this experiment it can be said that concentrations from 1 mM to 1nM must have been too high for an increase in root size, causing an excessive synthesis of ethylene instead and thus reducing it. Additionally, the highest levels may even be described as toxic, especially during embryogenesis when auxin concentrations are vital in setting further gene alterations for the differentiation of distinct plant parts.[55] Only the 10^{-8} M IAA solution seemed to be low enough so as to potentially increase the meristematic activity, loosening of cell walls and lateral root generation without inducing this adverse reaction. Hence, the investigation of concentrations ranging from for example 10^{-8} to 10^{-13} M could be subject to further research in order to examine the suggested trend line in Figure 18. As a last note, it is rather peculiar that no obvious alteration of the internode length could be observed in plants treated with IAA because those ought to have either inhibited shoot growth when too high or alternatively increased it when low enough, which should have most certainly be fulfilled with a 10^{-8} M solution. One possible and reasonable explanation for this occurrence might be that the induced ethylene production transported the IAA acquired through the roots continuously to the region of elongation, preventing its signalling in the internode. Another, less founded assumption would be that smaller roots prevent the growth of large plants as they supply the whole structure with nutrients, water and anchorage and therefore, potential hormonal enlargements of the internode are balanced.

4.2 Analysis of Results Relating to GA_3

4.2.1 Inference

Similarly to the IAA solutions, the addition of GA_3 could not provide a significant increase in root size at any concentration; however, all concentrations of GA_3 significantly decreased the area of the roots, with the most substantial reduction lying at 10^{-3} M and the smallest one at 10^{-7} M. Whether this peak at 10^{-7} M is actually sensible, remains questionable but this is elaborated upon later. Nevertheless, this clearly indicates that GA_3 has no capability of enhancing root growth but rather hampers its development, of which the reasons must be followingly further investigated.

4.2.2 GA Is Vital in Root Development but Not Particularly Promoting

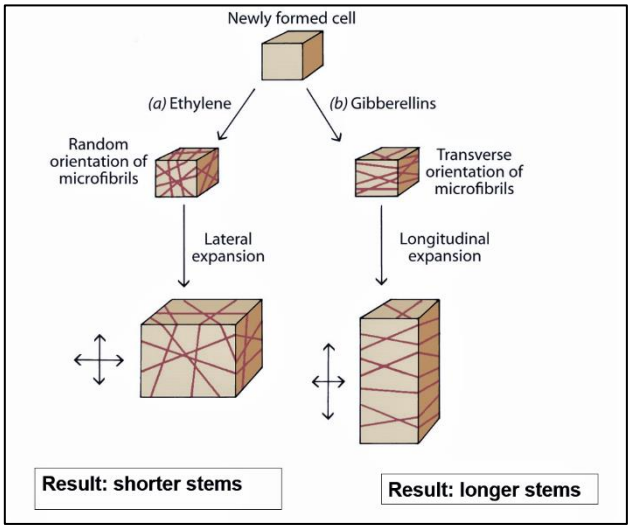
Conversely to auxins, gibberellins (GA) have not been as thoroughly studied in respect to their impacts on root structures. Nevertheless, what is known states that GA exists endogenously at a concentration of approximately 10^{-6} to 10^{-5} M in the roots, which is considerably less than the amount needed to induce changes in stems. This fact is very similar to the discussed auxin concentrations; however, in contrast to those, GA is believed to expresses so-called *saturation curves* (cf. Figure 22), meaning that only an absence would cause inhibition, meanwhile an abundance would simply reach a capacity of effect and not again a regulation as with auxins. Furthermore, this is illustrated when observing *na*-mutants, in which the intrinsic GA concentration is lowered to 10^{-6} by biosynthesis regulation and thus, it impeded root growth by roughly 50%. The crucial role of gibberellin in proper root elongation is ascribed to its effect on the correct orientation of cortical microtubules (CMT) as well as cellulose microfibrils (CMF), cell wall parts vital for its *elasticity or rigidness*. GA regulates their horizontal arrangement, allowing elongation while reducing extraordinary thickening, which in turn explains extreme swelling in gibberellin-deficient mutants. Additionally, GA exhibits regulatory influences on lateral root

[55] Cf. Jenik/Barton (2005), Internet

density. When investigating GA under-producing or insensitive mutants, some total of 1178 genes could be declared as significantly correlating with the number and lengths of formed lateral roots, most of which being associated with cell wall loosening, growth and proliferation. However, the inhibition itself could best be explained with GA upregulating in primordia the transcription of PIN9, a polar auxin transporter. Most probably it reduces the amount of auxin available in the lateral root nodes and thus the hormone promoting further growth, proving strong interconnections between the two phytohormones gibberellin and auxin, which are also present in the stem.[56]

A study conducted on *lemna minor* concluded that concentrations exceeding the usual 10^{-5} M quickly established a supra-optimal level of GA and thus negatively affected segments extracted from the roots' regions of elongation. Hence, there is a *very slim window* in which GA exhibits an advantageous behaviour, when considering that a promotion of growth may occur only at exogenous GA concentrations of 10^{-6} M and higher. The exact processes happening still need testing but on the one hand changes in osmotic pressures and CMT/CMF could be excluded as possible reasons, and on the other hand, the paper pronounces against a significant role of auxin in the sections elongation and thus, rejects the explanation of GA obstructing its signalling or transport. Another argumentation could be that toxically high amounts of GA mediate an exaggerated homeostasis response, a negative feedback, which is not restored to a normal level. This process is greatly controlled by so-called DELLA proteins, substances which act nearly exactly diametrically opposed to GA. In conclusion, this postulates GA acting in a similar manner as auxins in regard to concentrations, as both infra- and supra-optimal amounts cause inhibition of root growth. This opposes the previously mentioned theory of saturation curves.[57]

Figure 24: Different orientations of CMF or CMT caused by ethylene of gibberellins



Source: SlideServe (2012), slide 17 (colours edited)

[56] Cf. Gou et al. (2010), Internet; Tanimoto (2005), Internet
[57] Cf. Eckhardt (2007), Internet; Inada/Shimmen (2000), Internet; Tanimoto (2005), Internet

4.2.3 Concluding Explanation Regarding GA_3

The most sensible reasoning for these results would be the inhibitory effects on roots by GA, which were stated above, despite two of the tested concentration lying below the empirical threshold of 10^{-6} M. This may be explained with the hormone being added already during germination, at which point of time the organism is very susceptible to imbalances, and therefore, amounts of GA close to the limit of optimality would simply distort the intricate genetic mechanisms, irreversibly inhibiting further growth of roots. The stems then might not have been affected due to their needed concentrations for biochemical activity lying at much higher values. This argumentation can analogously be applied to the case of IAA. As for the peak at 10^{-7}, this may be neglected as the correlation of the change in root sizes and the one in concentration is not particularly significant to begin with, and therefore a flat line or one with a slight upward trend to the right could be assumed. Especially the latter scenario would be underpinned by previously proposed data because lower exogenous GA addition would mean a smaller surpassing of the threshold, which would then mean a larger final root size.

4.2.4 Sources of Errors

The most obvious limitation of this experiment's data is presented by the very small sample size. Notably, the mere three plants per concentration are absolutely prone to distortions by outliers, which additionally reduces the credibility of the performed scientific tests, and thus, a major improvement could be made by increasing the number of subjects. Furthermore, continuing with the specific experimental settings, one crucial flaw was the overflowing and mixing of the added solutions. Although great care was put into reducing this by both choosing a setup which maintained the smallest possible discrepancies between the concentrations of two adjacent subjects as well as adding the corresponding fluids in a cautious and slow manner with the intention of awaiting the complete absorption by the media, this overspilling and its effects could not be entirely prevented. Heavy rainfall often caused water build-up in the containers, most probably washing parts of the hormones out of the nurturing media and distributing them evenly, which would, for instance, provide the water control group with a small concentration of IAA. Unfortunately, precisely this, as it was lower than 10^{-8} M, was found to be most probably highly growth inducing and therefore negatively influenced the findings. As a countermeasure, the plants should have been cultivated in separate soils or at least together with equal concentrations of hormones had it been possible with the available means.

Besides that, in future experiments, lower concentrations of both hormones should be used, provided that GA was to be further investigated, with the intention of moving to more optimal concentrations and therefore determining the most potent one. Additionally, a more reasonable approach would include the watering with hormones only after they have passed the fragile process of embryogenesis. A last main deficiency was posed by the inaccuracy of the measuring devices and approaches. While the measuring cylinders and the balance appeared to be appropriately precise, the analysis of the photographs using photoshop remained rather flawed. Not only was there a basic variance in roughly 1000 pixels when assessing the number of pixels for the same area multiple times, but sometimes shadows could also not be properly eliminated, further causing misrepresentations. Besides that, the overlapping of some roots was inevitable, and the assessment of the boundary between internode and root structure was not always explicit due to under-expressed rosette leaves, forcing the resort to a decision based on discoloration, first root branching and location of former cotyledons. These issues could be ameliorated by waiting until the plants have reached a larger size so that other measuring approaches such as the one elucidated in the materials and methods section could be applied.

Other, in comparison minor, flaws include for one the differences in environmental conditions; despite the containers having been regularly exchanged in positions, the rain and exposition to the sun might have very well been distinct for each container. Moreover, the solutions were stored for the entirety of the two months in the pet bottles, meaning that they could decompose and react with the calcareous tap water, processes which were only partially reduced by them being stored in a dark and cool place. Lastly, the removal of the plants from the soil was rather problematic. On the one hand, detaching the unwanted subjects after 38 days could damage the chosen individual despite great caution. On the other hand, when removing the plants form their soils before the measurements, the occasional tearing of minute lateral roots or root hairs occurred unfortunately rather often due to their frailty.

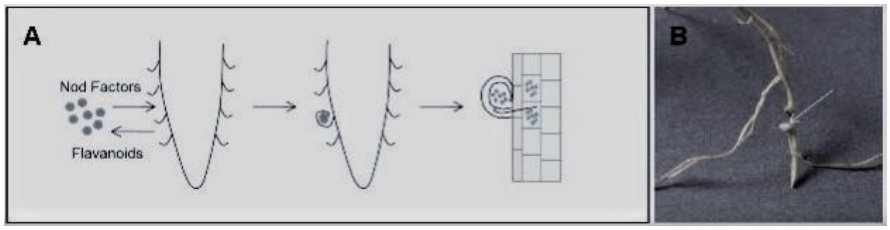
4.3 Ecological Assessment

4.3.1 Advantages of Enhanced Root Size

This and following subchapters seek by no means a completely detailed and entire listing of all facets comprised in the ecological root-soil interactions but it should instead supply a general overview and assessment of the potential impacts based on researched facts. One first substantial perk of enlarged root sizes or densities presents the ability to thrive in or resist nutrient-deficient environments. Enhanced root networks facilitate with their larger area for diffusion the uptake of the few ions present in the soil and thus enable the more efficient usage of available soil nutrients. Analogously, this may be applied to the obtaining of water. An enlarged surface area most certainly also supports the rate of diffusion of osmotically driven water inflow into the root and therefore plant structure, easing the organisms' comprehensive survival and growth. Thus, those individuals with more extensive underground networks exhibit a drought or also heat *resistance*, which is supported by research declaring increased root size as a reaction to aridity and thus an advantageous factor against these conditions as well.[58]

Furthermore, the effects of such a root alteration include the potential improvement of *symbiotic relationships* with other organisms ranging from fungi to bacteria and microbes. The larger the epidermal area of the plant's roots, the more numerous the possible places for attachment of beneficial fungi or alternatively the more root hairs, the larger the amount of potentially internalised rhizobacteria (cf. Figure 25).[59] Both these types of organisms furnish considerable or even essential support to the plant by breaking down organic compounds in the soil, mostly nitrogen-rich biochemicals with the consequence of plants being able to transport and utilise these. It should not be forgotten that the named symbionts groups contain various species and thus functions, especially fungi, in this case called mycorrhiza, consist of multiple subcategories. Examples contain arbuscular mycorrhiza protruding and infiltrating its host's cortical cells, while ectomy-

Figure 25: A: Schematic illustration of the internalisation of rhizobacteria by root hairs, thereafter they partake in processes such as nitrogen fixation inside the root. B: A root nodulation formed by this relationship



Source: Morgan/Connolly (2013), Internet (colours edited)

[58] Cf. Al Tawaha et al. (2017), Internet; Gruber et al. (2013), Internet; Sen/Tamar (n.y.) in Böhm/Kutschera/Lichtenegger (Eds.) (1982), p. 185-206
[59] Cf. Morgan/Connolly (2013), Internet

corrhizal fungi remain superficially attached. Besides the named nutritional advantage, they may possess anti-pathogenic qualities, or in the case of the latter group the strategy of ectomycorrhiza.[60] It occurs when at least two plants are connected by the hyphae of the same mycorrhiza, allowing the long-distance transportation of warning signals against threats or also organic compounds aiding plants in distress.[61]

Although the listed perks of increased root size are most certainly expedient for an individual plant's survival, there are as well fundamental gains on an ecological scope. Regularly, protection against erosion is mentioned as such an advantage. While roots create a firm anchorage for its remaining plant, in large quantities they maintain the cohesion of soils, which prevents their being torn away by the forces of nature, so-called *erosion*.[62] Closely linked to this effect is the root-mediated *water regulation* by means of facilitated seepage paired with the elevation of storage capacities. On the one hand, roots aerate the soil by mechanically penetrating it and generate water-absorbing humus when decomposed after death, factors contributing to the effective seepage of water so as to prevent inundations and similar threats. On the other hand, these two activities also help in the resorbed water's subsequent collection in upper soil layers, which enables later usage in drier periods.[63] These critical tasks of root networks are highly likely to be augmented with additional root volume. Additionally, they are becoming increasingly crucial due to the effects of global warming, those being on the one side heightened temperatures and thus dryness but on the other side also more extreme weather conditions, including floodings and heavy rainfall. As a last added value, plants' *nutritional role* may be considered. Not only the possibly increased epigeal size but also the one of the roots supply a broad range of animals with more nutrition, due to many species feeding upon roots as well. As for the humans' profit, vegetables such as turnips and carrots consist nearly entirely of the plant's roots, and therefore, the yield of these food sources would most probably rise in human cultivations, were the root size to be enhanced.

4.3.2 Threats of Enhanced Root Size

A large fraction of unfavourable side effects stemming from enlarged roots are linked with the means of creating them, that is the exogenic application of phytohormones or genetic modifications. Those aspects are going to be discussed in the following subchapter, meanwhile in this one, a selected array of potential, direct threats posed by enhanced roots is provided. A prominent one of these is the ecological overpopulation of the ground; as plants occupy larger volumes below them, a decreasing amount of unclaimed soil is available. Consequences may include a higher susceptibility to pathogenic transmissions or even epidemics, more rapid consumption of mineral salts and water as well as a lack of space for newly germing organisms. On balance, there is the potential of the soil quality vehemently deteriorating, imposing a constant stress situation onto all plants while exacerbating the formation of seedlings, which is additionally magnified by the acidity of roots' rhizosphere, the region encompassing them. What is more, unfavourable conditions such as the ones depicted above, often incentivise the plant to multiply its root size even more, conceivably instituting a positive feedback loop. Its result may also be disequilibria in the previously advantageous qualities of roots; for instance, the process of balancing water seepage and retention could possibly be disturbed by the increased water consumption, drying out soils, which then consequently lose their affinity for absorbing water, promoting floodings and similar processes.

[60] Cf. Bonfante/Genre (2010), Internet; de Kroon/Visser (Eds.) (2003), p. 263-267
[61] Cf. Simard et al. (1997), Internet
[62] Cf. Eder (n.y.) in Böhm/Kutschera/Lichtenegger (Eds.) (1982), p. 689-696
[63] Cf. Donner (n.y) in Böhm/Kuschera/Lichtenegger (Eds.) (1982), p. 667-670

Besides this destruction of natural equilibria and interactions, these enhanced roots, especially those of trees, may very well cause immediate damage to humanmade structures. Nowadays the rupturing of asphalt or streets, infiltration together with clotting of pipes (cf. Figure 26) and deformation of foundation soil confront many people with considerable expenses.[64] These cases of infrastructural damage would most certainly increase in frequency and magnitude, were tree roots to be artificially enhanced. Not only would this impose inconveniences in using such constructions, but financial liabilities could also cause significant strains for affected private people or authorities.

Figure 26: Incidence of severe root infestation in pipe system.

Source: D&NPlumbingServices (n.y.), Internet (colours edited)

4.3.3 Applications

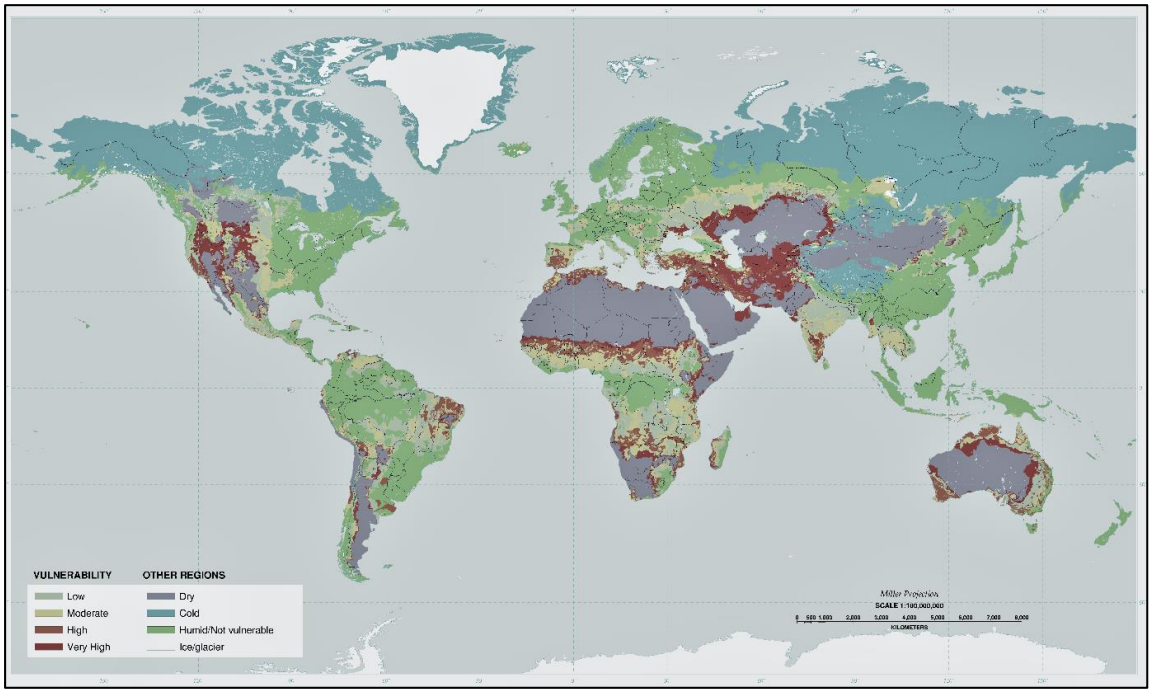
In the 1930s, enormous dust storms afflicted the American Great Planes. Formerly fertile agricultural land was swept away and carried as massive black sand blizzards across large parts of the contient. This fatal natural disaster, also referred to as the *dust bowl*, taught many approaches to combat extremely eroding conditions but also severe drought; two of which being the planting of vegetation in unutilised areas and the so-called residue management, a method comprising the act of leaving dead crop roots in agricultural fields until new seeds are sown.[65] Now that problems such as increasing temperatures, aridity and extreme weather conditions are facilitated by *global warming*, threats experienced 90 years ago may return to an even larger extent.[66] Especially the North American prairie, sub-Saharan desert and continental regions of Australia display high vulnerabilities to desertification caused by these developments (cf. Figure 27). However, also countries like Germany or other central European countries have experienced extraordinary dryness in recent years, destroying entire cultivated fields. [67]

As has been noted above, one of the attained techniques included the planting of shrubs and trees in unused but nevertheless vulnerable areas, which indicates that it is not completely absurd to manually alter natural vegetation for the sake of protection against erosion or drought. Plants possessing more extensive root systems than naturally common might demonstrate particularly high efficiency due to them being possibly capable of growing better in such unfavourable environments, as mentioned above. Thus, they can, on the one side, contribute to the cohesion of soil as well as a balanced water regulation so that the ground may recover and acquire a healthy humidity. On the other side, as this stronger underground support enables overall growth of the plant, it could ensure additional crop yield, aiding in the difficult agricultural circumstances in named regions. Especially the latter aspect presents a possibility which could equally be grasped in regions where this problem of desertification is not as

[64] Cf. TheMortonArboretum (n.y.), Internet
[65] Cf. History (2018), Internet
[66] Cf. Lynn (n.y.), Internet
[67] Cf. tagesschau (2018), Internet

devastating, but rather the requirement of augmenting agricultural productivity for a growing population provokes new obstacles.

Figure 27: Global map of vulnerability to desertification, ranging from red as very high risk to green, which indicated no real vulnerability



Source: USDA (1998), Internet (colours edited)

To stem the proposed introduction of modified plants, one could resort to the *exogenic application of phytohormones*, as was done in this paper. Hence, in the critical area, present plants, or perhaps newly cultivated ones, need to be regularly supplied with an appropriate hormone solution, which would be IAA in a concentration less than 10^{-8} M according to this paper. One major difficulty becomes immediately apparent here; water must be expended in regions where it is already scarce. Beside this tremendous disadvantage of this approach as well as its financial implications, the unknown long-term effects of phytohormones on ecological systems, not to mention humans and animals, must be considered. Despite some scattered findings such as the adverse effect of gibberellin on male rat fertility[68] or brassinosteroids' potential of fighting human breast carcinoma[69], no firm statement can be made about the changes induced by continuous addition of large masses of pure phytohormones to the environment. Not only would the life of other plants and soil organisms be at risk, but through the cycle of ground water, the exposition of humans to these biochemicals, whose impacts remain nearly unknown, would be inevitable. On balance, a wide-ranging and long-lasting treatment with phytohormones appears very inefficient as well as absolutely uncertain, thus potentially devastating. Conversely, usages in other, less vulnerable regions and in confined and controlled manners such as home gardens, greenhouses or even agricultural land seem nevertheless appropriate and indeed productive, which accords with the practice being common sight in these fields. This stems from the fact that they are in any case manually watered, meaning that no additional water needs to be expended for the enhancement of the roots. Furthermore, the scale and amounts are more strictly supervised in such defined frames, as opposed to a general application in the wild.

[68] Cf. Hosseinchi/Soltanalinejad/Roshangar (2013), p. 5-8
[69] Cf. Steigerová et al. (2010), p. 1-2

There is another mean to produce plants with enlarged roots where they may be needed: genetic modification. In contrast to the exogenic application, this includes the alteration of seeds, meaning that vegetation would need to be transported as mature plants, or alternatively entirely raised in desertifying planes. Thus, this strategy appears very costly and effort-stricken but in contrast to the prior one, it does not comprise the expenditures and continuous work linked with regular watering. Additionally, the introduction of genetically modified organisms (GMOs) into the wild remains vastly controversial. Both the ethical implications of producing and releasing humanmade life forms and the scientific doubts, namely regarding long-term consequences of germ line editing and ecological imbalances caused by artificially created advantages, contribute to this debate persisting as very heated. Hence, a factual resolution of this issue could by no means reached in this paper; however, a brief comment about its potential in the proposed context is made. Theoretically, amplifying genes responsible for the biosynthesis of certain PIN proteins or even IAA itself, could result in a long-term size increase, which in turn alleviates threats of desertification. Therefore, placing these genetically modified plants in the wild and awaiting their proliferation would certainly be an effective strategy, provided that the survival improving properties of the roots are sufficient to guarantee the young plants being capable of thriving in these harsh conditions. Additionally and analogously to before, this could also be applied agriculturally as crops would definitely profit from the consequent resistance to water or mineral salt scarcity, as seen at the example of an industrial GMO possessing higher capabilities of forming root hairs.[70] However, the counterarguments already presented above ought not to be forgotten. Especially the results linked to these plants displaying considerable superiority to wild type equivalents can be tremendously adverse. They would most certainly cause a shift in ecological balances, whose ultimate impact could by no means be entirely predicted. This is one of the reasons why the use of GMOs in general is heavily restricted, less in America and more in Europe, where only one specific maize mutant is allowed to be planted, and that not arbitrarily in the wild.[71]

In conclusion, both approaches appear rather unsustainable at the current state of research, although genetic modifications would promise a higher effectiveness. What has to be added regarding the extent of enhancement, however, is that a clear limit should be set, which may be explained with the threats proposed in the previous subchapter. As soon as the plant roots grow too large, be it through exogenic or endogenic alterations in hormone levels, their positive properties are lost or even reversed, the example of soil being additionally deprived instead of humidified applies here mainly. But here again, the exact threshold of size after which such developments are to be expected would need to be empirically established.

[70] Unger Baillie (2017), Internet
[71] transgen (2018), Internet

5 Conclusion

In this experimental framework, IAA at 10^{-8} M exhibited the most promising effects, despite the difference to the control group being non-significant. Therefore, this solution would provide a suitable approach to increase both the elongation of the root but also the number of lateral roots. However, due to the observed tendency of rising root sizes at lower concentrations, those as well as phytohormones like cytokinins should likewise be tested on their effectiveness. This would provide information on the overall most potent exogenic phytohormone treatment. As for GA_3, no indications for any capabilities of enlarging roots could be found; nevertheless, it may be assumed that the chosen concentrations were to such a degree too high that a trend as with IAA could have only been observed with more diluted solutions, as this would accord with recent studies in this field. In further experiments sources of errors such as the small sample size, the mixing of the different solutions or the inaccurate measurement of the root size via photographs should most certainly be avoided.

Applications of this knowledge could tackle an issue of international scope: global warming and consequent desertification. Enhanced roots provide the plants with survivability and the surrounding soil with regulatory processes enabling them to potentially decelerate or even reverse the developments in continuously drying environments. Furthermore, an appropriate mean of inducing these larger root networks is genetic modification. However, due to possibly tremendous drawbacks, this cannot be inconsiderately executed; a thorough assessment of the impact of such GMOs' introduction might evoke must be performed. Moreover, this would include empirically investigating at which sizes, roots would become rather detrimental than beneficial.

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Appendix

Raw and Intermediate Data

Test Group IAA

	Sample No.	1st Pic. [pixels]	2nd Pic. [pixels]	Mean of Pic. [pixels]
10^{-3} M	1	31451	37217	34334,0
	2	74542	47179	60860,5
	3	70082	60032	65057,0
	Arith. Mean $\bar{x}$			**53417,17**
	SD			**16659,17**
10^{-4} M	1	104027	90245	97136,0
	2	81066	62515	71790,5
	3	65130	56400	60765,0
	Arith. Mean $\bar{x}$			**76563,83**
	SD			**18649,42**
10^{-5} M	1	49408	49068	49238,0
	2	97306	113250	105278,0
	3	180335	152646	166490,5
	Arith. Mean $\bar{x}$			**107002,17**
	SD			**58645,26**
10^{-6} M	1	166113	202778	184445,5
	2	212054	220712	216383,0
	3	168840	191830	180335,0
	4	209489	193273	201381,0
	5	97771	96449	97110,0
	6	91324	103043	97183,5
	7	59319	93758	76538,5
	8	87783	90886	89334,5
	9	61782	61806	61794,0
	10	130015	141752	135883,5
	11	105760	94107	99933,5
	12	109613	110795	110204,0
	13	92852	76657	84754,5
	14	51848	73548	62698,0
	Arith. Mean $\bar{x}$			**121284,18**
	SD			**52785,07**
10^{-7} M	1	128251	175953	152102,0
	2	222809	239948	261378,5
	3	385742	378780	382261,0
	Arith. Mean $\bar{x}$			**265247,17**
	SD			**115128,26**
10^{-8} M	1	261336	381304	321320,0
	2	297603	263648	280625,5
	3	347293	337395	342344,0
	Arith. Mean $\bar{x}$			**314763,17**
	SD			**31377,34**

Test Group GA_3

	Sample No.	1st Pic. [pixels]	2nd Pic. [pixels]	Mean of Pic. [pixels]
10^{-3} M	1	33048,0		33048,0
	2	48480,0		48480,0
	3	9598	8693	9145,5
	Arith. Mean $\bar{x}$			**30224,50**
	SD			**19818,67**
10^{-4} M	1	14640	17147	15893,5
	2	80478	80826	80652,0
	3	71742	57387	64564,5
	Arith. Mean $\bar{x}$			**53703,33**
	SD			**33717,79**
10^{-5} M	1	63908	29642	46775
	2	50469	59672	55070,5
	3	70106	51331	60718,5
	Arith. Mean $\bar{x}$			**54188,00**
	SD			**7013,52**
10^{-6} M	1	62571	91156	76863,5
	2	32749	32652	32700,5
	3	77020	55176	66098,0
	4	68811	91839	80325,0
	5	68777	76637	72707,0
	6	67356	86152	76754,0
	7	75471	108772	92121,5
	8	63195	60740	61967,5
	9	86449	78103	82276,0
	10	71723	65970	68846,5
	11	82900	70684	76792,0
	12	58189	64955	61572,0
	13	55820	66321	61070,5
	14	87175	51849	69512
	Arith. Mean $\bar{x}$			**69971,86**
	SD			**13912,29**
10^{-7} M	1	91180	49735	70457,5
	2	82194	69780	75987,0
	3	111692	103154	107423,0
	Arith. Mean $\bar{x}$			**84622,50**
	SD			**19938,43**
10^{-8} M	1	76904	55843	66373,5
	2	86952	70018	78485
	3	56041	48505	52273,0
	Arith. Mean $\bar{x}$			**65710,50**
	SD			**13118,57**

Control Group Water

Sample No.	1st Pic. [pixels	2nd Pic. [pixel	Mean of Pic. [pixels]
1	443902	337689	390795,5
2	139333	199788	169560,5
3	370865	198518	284691,5
4	145149,0		145149,0
5	351248	309002	330125,0
6	321145	297360	309252,5
7	246390	188885	217637,5
8	249298	203743	226520,5
9	232702	224660	228681,0
10	307417	253087	280252,0
11	88739	93058	90898,5
12	118797	140198	129497,5
13	312000	387569	349784,5
14	355490	343764	349627
Arith. Mean $\bar{x}$			**250176,61**
SD			**92448,11**

Experimental Part 1A,

Intermediate Results for Student's *t*-tests

IAA - W	Sample No.	D (IAA-W)	D^2 ((IAA-W)²)
	1	-2,06E+05	4,26E+10
	2	4,68E+04	2,19E+09
	3	-1,04E+05	1,09E+10
	4	5,62E+04	3,16E+09
	5	-2,33E+05	5,43E+10
	6	-2,12E+05	4,50E+10
	7	-1,41E+05	1,99E+10
	8	-1,37E+05	1,88E+10
	9	-1,67E+05	2,79E+10
	10	-1,44E+05	2,08E+10
	11	9,04E+03	8,16E+07
	12	-1,93E+04	3,72E+08
	13	-2,65E+05	7,02E+10
	14	-2,87E+05	8,23E+10
	Sum:	**-1,80E+06**	**3,99E+11**

GA_3 - W	Sample No.	D (GA3-W)	D^2 ((GA3-W)²)
	1	-3,14E+05	9,86E+10
	2	-1,37E+05	1,87E+10
	3	-2,19E+05	4,78E+10
	4	-6,48E+04	4,20E+09
	5	-2,57E+05	6,63E+10
	6	-2,32E+05	5,41E+10
	7	-1,26E+05	1,58E+10
	8	-1,65E+05	2,71E+10
	9	-1,46E+05	2,14E+10
	10	-2,11E+05	4,47E+10
	11	-1,41E+04	1,99E+08
	12	-6,79E+04	4,61E+09
	13	-2,89E+05	8,34E+10
	14	-2,80E+05	7,85E+10
	Sum:	**-2,52E+06**	**5,65E+11**

IAA - GA	Sample No.	D (IAA-GA3)	D^2 ((IAA-GA3)²)
	1	1,08E+05	1,16E+10
	2	1,84E+05	3,37E+10
	3	1,14E+05	1,31E+10
	4	1,21E+05	1,47E+10
	5	2,44E+04	5,96E+08
	6	2,04E+04	4,17E+08
	7	-1,56E+04	2,43E+08
	8	2,74E+04	7,49E+08
	9	-2,05E+04	4,20E+08
	10	6,70E+04	4,49E+09
	11	2,31E+04	5,36E+08
	12	4,86E+04	2,37E+09
	13	2,37E+04	5,61E+08
	14	-6,81E+03	4,64E+07
	Sum:	**7,18E+05**	**8,34E+10**

Experimental Part 1B

Intermediate Results and Organisation for R^2-value calculation

	-log conc. (x)	IAA (y_1)	GA_3 (y_2)		IAA: xy_1	IAA: x^2	IAA: y_1^2		GA_3: xy_2	GA_3: x^2	GA_3: y_2^2
	3	3,43E+04	3,30E+04		1,03E+05	9,00E+00	1,18E+09		9,91E+04	9,00E+00	1,09E+09
	3	6,09E+04	4,85E+04		1,83E+05	9,00E+00	3,70E+09		1,45E+05	9,00E+00	2,35E+09
	3	6,51E+04	9,15E+03		1,95E+05	9,00E+00	4,23E+09		2,74E+04	9,00E+00	8,36E+07
	4	9,71E+04	1,59E+04		3,89E+05	1,60E+01	9,44E+09		6,36E+04	1,60E+01	2,53E+08
	4	7,18E+04	8,07E+04		2,87E+05	1,60E+01	5,15E+09		3,23E+05	1,60E+01	6,50E+09
	4	6,08E+04	6,46E+04		2,43E+05	1,60E+01	3,69E+09		2,58E+05	1,60E+01	4,17E+09
	5	4,92E+04	4,68E+04		2,46E+05	2,50E+01	2,42E+09		2,34E+05	2,50E+01	2,19E+09
	5	1,05E+05	5,51E+04		5,26E+05	2,50E+01	1,11E+10		2,75E+05	2,50E+01	3,03E+09
	5	1,66E+05	6,07E+04		8,32E+05	2,50E+01	2,77E+10		3,04E+05	2,50E+01	3,69E+09
	6	1,84E+05	7,69E+04		1,11E+06	3,60E+01	3,40E+10		4,61E+05	3,60E+01	5,91E+09
	6	2,16E+05	3,27E+04		1,30E+06	3,60E+01	4,68E+10		1,96E+05	3,60E+01	1,07E+09
	6	1,80E+05	6,61E+04		1,08E+06	3,60E+01	3,25E+10		3,97E+05	3,60E+01	4,37E+09
	6	2,01E+05	8,03E+04		1,21E+06	3,60E+01	4,06E+10		4,82E+05	3,60E+01	6,45E+09
	6	9,71E+04	7,27E+04		5,83E+05	3,60E+01	9,43E+09		4,36E+05	3,60E+01	5,29E+09
	6	9,72E+04	7,68E+04		5,83E+05	3,60E+01	9,44E+09		4,61E+05	3,60E+01	5,89E+09
	6	7,65E+04	9,21E+04		4,59E+05	3,60E+01	5,86E+09		5,53E+05	3,60E+01	8,49E+09
	6	8,93E+04	6,20E+04		5,36E+05	3,60E+01	7,98E+09		3,72E+05	3,60E+01	3,84E+09
	6	6,18E+04	8,23E+04		3,71E+05	3,60E+01	3,82E+09		4,94E+05	3,60E+01	6,77E+09
	6	1,36E+05	6,88E+04		8,15E+05	3,60E+01	1,85E+10		4,13E+05	3,60E+01	4,74E+09
	6	9,99E+04	7,68E+04		6,00E+05	3,60E+01	9,99E+09		4,61E+05	3,60E+01	5,90E+09
	6	1,10E+05	6,16E+04		6,61E+05	3,60E+01	1,21E+10		3,69E+05	3,60E+01	3,79E+09
	6	8,48E+04	6,11E+04		5,09E+05	3,60E+01	7,18E+09		3,66E+05	3,60E+01	3,73E+09
	6	6,27E+04	6,95E+04		3,76E+05	3,60E+01	3,93E+09		4,17E+05	3,60E+01	4,83E+09
	7	1,52E+05	7,05E+04		1,06E+06	4,90E+01	2,31E+10		4,93E+05	4,90E+01	4,96E+09
	7	2,61E+05	7,60E+04		1,83E+06	4,90E+01	6,83E+10		5,32E+05	4,90E+01	5,77E+09
	7	3,82E+05	1,07E+05		2,68E+06	4,90E+01	1,46E+11		7,52E+05	4,90E+01	1,15E+10
	8	3,21E+05	6,64E+04		2,57E+06	6,40E+01	1,03E+11		5,31E+05	6,40E+01	4,41E+09
	8	2,81E+05	7,85E+04		2,25E+06	6,40E+01	7,88E+10		6,28E+05	6,40E+01	6,16E+09
	8	3,42E+05	5,23E+04		2,74E+06	6,40E+01	1,17E+11		4,18E+05	6,40E+01	2,73E+09
Sum:	**165**	**4,15E+06**	**1,84E+06**		**2,63E+07**	**9,93E+02**	**8,48E+11**		**1,10E+07**	**9,93E+02**	**1,30E+11**

Kantonsschule Büelrain
Winterthur

Maturitätsarbeit 2018
Ehrlichkeitserklärung

Name Lange Vorname Nils Klasse 4eW

Titel der Arbeit Artificial Root Enhancement

Hiermit erkläre ich, dass ich die vorliegende Arbeit nach den üblichen Gepflogenheiten des wissenschaftlichen Arbeitens verfasst habe, d.h. im Besonderen:

- Ich habe diese Arbeit selbständig verfasst.
- Alle Hilfsmittel, die ich verwendet habe, sind angegeben.
- Alle wörtlichen und sinngemässen Übernahmen aus anderen Werken sind als solche gekennzeichnet.
- Personen, die einen wesentlichen Beitrag zu dieser Arbeit geleistet haben (Betreuer/-in ausgenommen), habe ich ebenfalls erwähnt.

Zutreffendes bitte ankreuzen

☒ Ich stelle meine Arbeit zu Demonstrationszwecken der Mediothek der KBW zur Verfügung.

☐ Meine Arbeit darf nicht zu Demonstrationszwecken verwendet werden.

Datum 8. Dezember 2018 Unterschrift Nils Lange