Extension Education Methods

EduAPPLE: Interactive Teaching Tool for Apple Tree Crown Formation

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SUMMARY. In central Europe there are many backyard fruit growers who receive no proper education about fruit tree care. Their knowledge is mostly based on various handbooks and learning through trial and error. Such learning is slow and can even result in damage to the tree. To shorten the learning time, a new interactive teaching tool EduAPPLE has been developed based on the basic laws of apple tree (*Malus × domestica*) growth and training. Pruning, weighting, tying, and spreading can be interactively practiced over and over again without any danger to the actual trees. Training responses are immediately seen and are analogous to those of real trees. They are not only predetermined by a set of rules, but also calculated based on the changes the actions cause to the light interception of the tree. EduAPPLE enables high-quality views of trees and their light interception from all angles in real time and is designed for education regarding free-standing apple tree training (spindle). It can, therefore, be used in schools, universities, and other educational organizations, as well as by tree growers, including the large number of growers having only a few fruit trees.

Most home fruit growers acquire the necessary knowledge on fruit tree care from horticultural handbooks in combination with tree training courses. The learning process is therefore slow and meanwhile trees are often inadequately cared for. Although many kinds of fruit trees can be found in these gardens, the most common are apple trees of various cultivars and rootstocks, most of which are free standing and trained in the spindle form (Tojnk et al., 2011). Pruning

has a direct influence on tree form development, growth intensity, time to yield, the balance between growth and fruiting, and renovation of bearing wood and, along with bending, is necessary in both intensive fruit production and free-standing tree forms (Lakso and Corelli Grappadelli, 1991; Unuk et al., 2008; Wünsche et al., 2000).

To make the learning process faster and easier, the interactive education application EduAPPLE (Kohek et al., 2015) has been developed,

where tree-training techniques can be applied on three-dimensional (3D) apple tree models. The user can see the tree from different directions and freely rotate it while performing the desired operations. The application then simulates tree response to these actions. It allows 3D simulation of tree training toward the desired shape, which saves costs and allows training in regions (e.g., cities) where travel to an orchard is not practical. It is also ideal for introducing students to the effects of horticultural manipulation on apple trees.

The application is based on the new growth model, originating in the work of Paubicki et al. (2009), where tree growth is defined by the reaction of buds to available resources (light, water, nutrients, and assimilates). Pruning and branch positioning change the growing conditions by redistributing resources to the remaining branches. Therefore, our approach to tree light interception and growth resources redistribution enables fast, realistic, and autonomous responses to pruning and branch positioning. The consequence is a user-independent pruning and bending response true to that documented in the literature. The results become visible in the next growing season when new shapes are formed as trees respond to the realized actions.

Since potential users apply various cultivars and rootstocks and differ in their use of plant protection products, we used the same approach as that already found in tree pruning handbooks and show only the most common tree responses in the form of changes in tree crown structure without predicting fruit load or quality. An average user is not expected to have the large amount of information necessary for the crop amount prediction (Lauri and Lespinasse, 2001; Lauri et al., 1996, 2011; Wünsche et al., 2000). Therefore, our aim is to provide a general understanding of tree training techniques and their influence on tree light interception and thus the yield potential for fruit crops (Stephan et al., 2008).

For better evaluation of training actions, tree light interception and

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Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
2.54	inch(es)	cm	0.3937

light distribution through the canopy can be examined by the use of implemented visualization. To perform all the necessary operations in real-time, a graphics-processing unit is used to complete the most complex parts of the computation.

The first virtual reality system for growth following the pruning of apple trees was based on apple trees digitized from orthogonal photographs (Atkins et al., 1996). Like the majority of early pruning simulators, the Atkins' simulator was driven by a rule-based model, with predefined pruning responses without consideration of actual shading effects.

Because of their rigidity, rule-based models were later replaced by functional-structural plant models. SIMWAL was one of the first structural-functional tree models developed for training walnut trees [*Juglans regia* (Balandier et al., 2000)]. It simulated the 3D structural dynamics of a tree and biomass partitioning among its internodes, buds, leaves, and roots over a period ranging from a few months to several years according to climatic conditions [temperature, radiation, and air carbon dioxide (CO₂) concentration] and pruning. Their approach was quite accurate but slow, thus preventing its usage in real-time applications.

L-PEACH is an L-system (Lindenmayer, 1968; Prusinkiewicz and Lindenmayer, 1990) based functional-structural probabilistic model that helps to understand peach tree (*Prunus persica*) growth and fruiting (Lescourret et al., 1998; Lopez et al., 2010; Smith et al., 2008). This model integrates important concepts related to carbon assimilation and distribution. It includes the modeling of responses to tree pruning and fruit thinning. 3D depictions of simulated tree growth are displayed on a computer screen and the user can easily interact with the model.

Another L-system based simulator, MAppleT, was introduced by Costes et al. (2008) to simulate the apple tree development in interaction with gravity. The authors combined stochastic models to simulate the tree topology and the mechanistic model for its geometry.

Lang and Lang (2008) created VCHERRY—a sweet cherry tree (*Prunus avium*) growth model for testing training decisions by predicting

resulting fruit amounts. Fruit amount is also influenced by different selections of rootstocks, soil types, and regional climates, as predefined in the application.

A computer model for pruning practices regarding apple trees using a Hidden Semi-Markov Chain was described by Xia et al. (2009). This system can simulate several growth situations with direct feedback from different levels of pruning schemes. Environmental effects such as light reception were not considered in their work, limiting the simulation of larger trees, where self-shading becomes an important factor for tree growth.

A competition-based model of pruning apple trees based on L-systems within the powerful OpenAlea framework was introduced by Cokelaer et al. (2010) and Pradal et al. (2008). As only basic physiological processes are included, it is possible to estimate the parameters to fit the growth of control trees and to reproduce a realistic relationship to pruning. The use of their framework is quite complex, making their tool impractical for educational purposes.

More advanced functional-structural tree growth models consider significantly more factors than those that are self-organizing but are slower and therefore also inappropriate as an interactive education tool. In contrast, our model is fast and fully autonomous as it works in a self-organizing way. Therefore, it can be applied to trees of any age and to branches at any position or orientation.

Materials and methods

GROWTH MODEL. Apple tree growth is a complex process that has been the subject of numerous studies over many years (Avery, 1969; Kato and Ito, 1962; Lauri and Lespinasse, 2001; Lauri et al., 2011; Rogers and Vyvyan, 1928). Tree growth is determined by many factors, the most important being rootstock selection, tree age, fruiting in the previous season, and climate. To provide an adequate tree growth model for the EduAPPLE teaching tool, we searched for the most common features in apple tree growth to create a model general enough for our purposes. Vegetative growth is controlled by hormones such as gibberellins and auxins, which promote or inhibit bud growth, cell division and elongation (Cline, 1991),

and stem growth. They are also responsible for conditions known as apical dominance and gravimorphism.

In the search for an appropriate existing tree growth model, it was found that Paľubicki's model (Paľubicki et al., 2009) generated very realistic 3D tree models and distinguished between terminal and auxiliary buds. It also incorporated apical dominance and a basic type of bud dormancy. Paľubicki's model is based on the Borchert–Honda (BH) model (Borchert and Honda, 1984), who successfully replaced the “inhibitor” and “promotor” rates within a tree with the concept of different “flow rates” among branches. A lower flow rate means less resources to the buds and thus slower growth and can be calculated by using simple rules. In Paľubicki et al. (2009), the tree is therefore assembled from interconnected internodes and buds (Fig. 1A). The first metamer represents the base of the tree. New metamers grow out of buds, whereas new leaves are formed out of bud axils.

To determine which buds will develop into shoots and which will stay dormant in Paľubicki et al. (2009), the amount of light received by buds is calculated as the equivalent to the later photoassimilates and serves as a measure for the available growth-inducing resources. However, assimilate allocation is a dynamic process involved in a number of feedback processes which are very hard to simulate (Lacointe, 2000). To overcome that, the authors used the extended BH and priority models to distribute the total amount of available resources back to the buds. The buds therefore develop into shoots if the amount of received resources is high enough. The overall growth algorithm is presented in Figure 1B where the tree growth is controlled by competition among buds with their leaves for light and space.

Although the model of Paľubicki et al. generated trees true to reality, it did not respond well to the changes associated with tree training actions. Therefore, major modifications were required in the resource redistribution among different buds. Because of the lack of data on the cultivar, the rootstock, the climate, or the crop load in the previous season, the crop amount and consequently its effects on the vegetative growth cannot be predicted

Fig. 1. (A) Apple tree structure elements used in the tree synthesis algorithm. The point at which one or more leaves are attached to a stem is a node and the part of the stem between two nodes is an internode. Terminal and lateral buds are located at the ends of newly grown internodes, while on the other internodes only the lateral buds are located. An internode with attached buds and leaves forms a metamer. Nodes on branches form a hierarchical structure (e.g., node 2 is a child of node 1). The nodes located closer to the stem are regarded as parents of those farther away. (B) Schematic view of self-organizing tree model simulation steps.

(Avery, 1969; Costes et al., 2003; Lauri et al., 1996; Wünsche et al., 2000).

RECEIVED LIGHT CALCULATION. The main source for all available resources is the amount of received light, which must be calculated for each leaf. If a leaf lies under metamers, its amount of received light is diminished. In the Pałubicki model the authors used the shadow propagation algorithm for this purpose. Their approach requires a large amount of memory and its discrete nature lowers calculation accuracy. To address the described deficiencies, the algorithm needed to be simplified by directly calculating the shadow quantity $\Delta s_{i,j}$ that the j -th leaf receives by the i -th leaf or internode:

$$\Delta s_{i,j} = \frac{1}{80} \left\{ 0.5 \tanh \left(\frac{1}{\|p_i - p_j\|} \right) + 0.5 \frac{0.2(p_{i,y} - p_{j,y})}{\sinh[2\|p_{i,xz} - p_{j,xz}\| + 0.2(p_{i,y} - p_{j,y})]} \right\}, \quad [1]$$

where, p_i represents a position of the i -th internode/leaf and p_{xz} represents a two-dimensional vector without the altitudinal component. $\Delta s_{i,j}$ ranges from 0 to 1/80, which is an empirically chosen value, meaning each internode/leaf casts only a small portion of shadow. To prevent collisions between branches, $\Delta s_{i,j}$ increases with decreasing distance between the j -th leaf and i -th internode in cases where both have the same height. If $p_{j,y} > p_{i,y}$, the value 0 is returned instead.

The overall amount of shadow the j -th leaf receives is calculated by:

$$s_j = \min \left(\sum_{i \in I} \Delta s_{i,j} - \frac{1}{80}, 1 \right), \quad [2]$$

where the set I represents all internodes and leaves. To prevent the self-shading effect, the value 1/80 is subtracted. The amount of “photosynthesis product” q_j regarding the j -th leaf is calculated as:

$$q_j = C - s_j, \quad [3]$$

where $C = 1$ represents the amount of the photosynthesis product of a non-shaded leaf. Finally, the total amount of photosynthesis product, Q , is calculated by the summation of photosynthesis product of each leaf q_j .

RESOURCES DISTRIBUTION. Roots acquire an amount of water and nutrients in relation to an accumulated value of photosynthesis product, which defines the total amount of available resources calculated by the next equation:

$$v = \alpha Q, \quad [4]$$

where α represents the “efficiency for utilizing a photosynthesis product” and Q the accumulated photosynthesis product. The amount of available resources regulates both vegetative and reproductive growth as was well documented by Costes et al. (2003). The parameter α is shaped to follow their observations and is defined by the following equation:

$$\alpha = 40 \tanh(0.2/y) + 2, \quad [5]$$

where y is a tree’s age in years.

Next, the calculated available resources v have to be distributed to the buds. In the Pałubicki model the resources are divided between the branches. This division, however, is also the greatest weakness of their approach since it does not respond well to changes in tree structure.

A new model is therefore introduced where the calculation is executed at the level of the buds. To do that, the share of resources w_i in relation to the position of bud i in the tree has to be calculated using the following equation:

$$w_i = q_i \left[4(2 - \bar{n}_i) + 4(1 + \bar{h}_i)^2 \right] \tanh(1/\bar{\beta}_i)^{6/\bar{\beta}_i}, \quad [6]$$

where, $\bar{n}_i$ is the normalized number of internodes between the bud’s base and bud i , $\bar{h}_i$ is the normalized height of bud i , and $\bar{\beta}_i$ is the normalized angle between the bud orientation and the vertical axis.

Equation [6] incorporates both principles: apical control and gravimorphism (Wareing and Nasr, 1961). For all the branches $\bar{n}_i$ has the highest values in terminal buds, which increase with the higher positioning of branches. Bud elevation is further emphasized by the parameter $\bar{h}_i$ where $\bar{h}_i = 1$ represents the highest bud on the tree.

Borchert and Honda (1984) showed that the branching angle is of equal importance. To include this in our new model, the angle enclosed by the bud’s orientation vector and the vertical axis, $\beta \in [0^\circ, 180^\circ]$ is used. By normalizing this angle a value $\bar{\beta}_i$ is obtained. The parameter w_i therefore favors high upwards-oriented terminal buds, which encourage a strong central leader and the growth of watersprouts by controlling the resource distribution. The amount of resources v_i each bud i receives from the total amount is thus defined by the next equation:

$$v_i = v \frac{w_i}{\sum_{j \in S} w_j}, \quad [7]$$

where S represents the set of all buds. The presented formula remains stable also when altering the crotch angles of branches and even when they are partially or completely removed.

Buds with $v_i \geq 1$ have the potential to shoot. Dormancy completion of

buds is not a simple process and depends on many factors (Lauri et al., 2008). In the literature two different approaches to the mentioned problem can be found: by allowing only every k -th bud to grow ($w_i = 0$ if $i \bmod k \neq 0$) or by using Markov chains (Balandier et al., 2000). In EduAPPLE both approaches are implemented and the user can choose between them. In both cases the buds located on the wood older than 1-year shoot with 50% lower probability.

Tree size depends strongly on the rootstock selection (Lauri et al., 2011); therefore, the right side of Eq. [7] is multiplied with $\tanh(500/n_i)^{n_i}$. This has the effect of limiting tree size to 5 m [$\max(n_i) \leq 166$], which is the typical size of trees on vigorous rootstock. The parameter n_i represents the number of internodes between the i -th bud and the roots.

GROWTH OF NEW SHOOTS. In relation to received amounts of resources, each bud shoots $\lfloor v_i \rfloor$ metamers of 3 cm in length. The direction of new shoots is determined by the direction $\mathbf{v}_p$ of parent buds modified by the weighted random direction $\mathbf{v}_r$ and the direction $\mathbf{v}_g$ pointing toward the ground. To demonstrate the effects of different training techniques on tree crown development, the weight on a random direction is set to 0. The weight for the direction toward the ground is set to -0.02 to achieve the effect of photomorphism. The new direction is thus calculated as the weighted sum of $\mathbf{v}_p$, $\mathbf{v}_r$, and $\mathbf{v}_g$.

To promote realism, the internodes have to be equipped with diameter values as the branches do not only grow in length, but also become thicker. The diameter of each internode is calculated as the rooted sum of the exponentiated diameters of

the main and lateral descendant internodes.

As the diameters of the internodes depend on the diameters of the child internodes, the pruning operation could cause the internode diameters to shrink. To prevent this, the diameter of the internode i is calculated as:

$$d_i = \max \left[d_{i,old}, \left(d_{i,l}^3 + d_{i,m}^3 \right)^{1/3} \right], \quad [8]$$

where $d_{i,l}$ represents the diameter of the lateral branch and $d_{i,m}$ that of the main branch.

To display trees, their geometry is generated from the topological tree data and sent to the graphics processing unit (GPU). The leaves are displayed in the places of less than 2-year-old buds while older buds are covered by the trunk.

IMPLEMENTATION. Our implementation is realized in the programming language C++, and the visualization engine is based on Open Graphics Library (OpenGL). Trees are represented by a recursive structure where each internode points to the main and lateral internode or bud. Each internode contains additional data (e.g., diameter, position, orientation, rotation, received light, and received resources) that enables flexibility and further extensions.

Since, the calculation of received light is time consuming, it is implemented in Open Computing Language (OpenCL) to use the parallel nature of central processing units (CPUs) and GPUs.

An interactive response was implemented for bending, spreading, and weighting by using inverse kinematics similar to Power et al. (1999).

Results

EduAPPLE enables various tree training techniques and their evaluation by using light interception, water distribution, received photosynthesis products, or shadow space visualization.

BRANCH POSITIONING. There are three general methods for branch positioning, all of which are interactively implemented: spreading, tying, and weighting (Fig. 2A and C). First a user selects a position on a branch to change and then pulls the selected branch into the desired position by weighting, tying, or spreading. In the next season the altered tree is shown. In the case of spreading, new green shoots have grown mostly at higher positions on the previously bent branch (Fig. 2B).

Our tool clearly demonstrates the importance of the proper positioning of a weight on a branch. The more the weight is placed away from the trunk, the more the branch is bent, sometimes even too much (Fig. 2C). Then the branch bends down in an arc, which is undesirable because it produces vigorous shoots at the highest point of the branch and very short ones at the branch end (Fig. 2D); in contrast, correctly weighted branches provide more vigorous and better placed shoots at their ends.

To bend branches optimally it is important to measure the crotch angles of branches. EduAPPLE therefore supports interactive crotch angle measurement between two branches that the user selects. With this tool the user can easily study the effects of branch slope on tree growth. As it is hard to estimate the length of branches on a computer screen, a simple functionality has been added for

Fig. 2. Apple tree training examples: (A) branch spreading in second growing year (spindle form), (B) the tree after 1 year, (C) weighting the 2-year-old tree, and (D) the weighted tree 1 year later.

Fig. 3. Apple tree responses to different cuts: (A) 3-year-old tree, (B) 3-year-old thinned-cut tree, (C) 3-year-old headed tree, (D) unpruned tree after 1 year, (E) thinned-cut tree after 1 year, and (F) headed tree after 1 year.

Fig. 4. Light interception of (A) older untrained and (B) pruned apple tree toward the open vase form. The darker shade represents smaller quantities of intercepted light (Eq. [3]).

measuring it. When the user clicks on both points on the screen, the length is calculated and displayed.

PRUNING. Tree pruning is implemented interactively. The user clicks on a point on a branch to cut (Fig. 3A), afterward the branch is pruned and the pruning point is marked with a line segment (Fig. 3B). The pruned branches are still visible but with lesser intensity. The consequences of pruning can be seen during the next growing season (Fig. 3F). In close-up view, a saw can be seen instead of a line, which additionally provides an enhanced visual representation.

Tree training mainly uses two kinds of pruning. One is a thinning cut (Fig. 3B) (Harris, 1994), that opens and forms a more comprehensive canopy and promotes strong branches. In our tool this is clearly shown (Fig. 3E) in relation to an unpruned tree (Fig. 3D). The second one is a heading (topping) cut (Fig. 3C) (Harris, 1994), that promotes

the growth of lower buds and makes the tree denser (Fig. 3F). A user can also learn all these facts from textbooks, but with EduAPPLE he/she can actually cut any branch on the tree and then observe the consequences. The user can experiment with different cuts over and over again.

The most important role of pruning in the canopy management process is to maximize light interception and ensure good light distribution since high light interception and its distribution throughout the canopy are the pillars of tree productivity (Stephan et al., 2008). Therefore, the pruning results can also be evaluated by studying light penetration into the tree's crown, which is one of our auxiliary tools shown in Figure 4.

In Figure 4A a tree without the pruning can be seen, where only the outer branches receive a fair amount of light, but by pruning toward an open vase form, most of the branches are well lit (Fig. 4B). In addition, EduAPPLE also calculates overall tree

crown light interception and changes in the tree crown light distribution during the training process.

EXAMPLE OF TRAINING PROCESS.

The training process of an apple tree from a 1-year-old unbranched whip toward a central leader growing form is presented to demonstrate the use of our teaching tool, as this growing form is quite common (Elfving et al., 1990; Stephan et al., 2008).

The training process is started on a 1-year-old apple tree, where only the tip of the shoot is cut off. In year 2, the training is continued with several cuts to prevent the upper shoots from overgrowing the lower branches (Fig. 5A). Shaded lower shoots are removed and five shoots are chosen to form scaffold branches. To preserve a desirable form similar to that of a pine tree, all the secondary shoots are consequently bent down (Fig. 5B).

To go on with the training, the upper shoots are shortened and the upgrowing shoots are removed (Fig. 5C). At the end the new shoots need to be bent (Fig. 5D). After 1 year, the training is continued by pruning the upgrowing shoots and limiting the lengths of branches (Fig. 5E). Other new shoots need to be weighted toward a horizontal orientation (Fig. 5F).

The training result in the fifth year is the conical-shaped tree (Fig. 5G) where the preservation of the central leader form can be continued. Figure 5H clearly shows that the outer branches receive greater amounts of light. In contrast to Figure 4A, much higher light penetration into the inner lower branches can be seen, which is promoted by spiral form branch arrangement. Consequently, a greater portion of the tree receives a higher amount of light. At the same time the expected low light

Fig. 5. Apple tree training toward central leader (A) of a 2-year-old tree by pruning and (B) weighting. Training toward central leader of a 3-year-old tree by (C) pruning and (D) weighting. Training toward central leader of a 4-year-old tree by (E) pruning and (F) weighting. (G) Trained 5-year-old tree toward central leader and (H) its light interception. The darker shadow represents smaller quantities of intercepted light.

penetration can be observed (Fig. 5H) due to overcrowding of branches at the bottom of the tree, as has already been documented by Elfving et al. (1990).

TRAINING SYSTEM EVALUATION. To evaluate the tree training system, we evaluate overall tree crown light interception. In the literature a silhouette to total area ratio (STAR) is often used in the case of 3D tree models (Stephan et al., 2008; Willaume et al., 2004). However, evaluating light interception with STAR values is complex and can be therefore very confusing for nonexperts. Since we already calculated the amount of light for each leaf in Eq. [3], we propose a new and more understandable metric for light interception, namely overall tree crown light interception, ω , defined as:

$$\omega = \frac{\sum_{i \in S} q_i}{|S|}. \quad [9]$$

ω is intuitive and therefore easy to understand. It ranges from a value of 0

for leaves with almost no illumination to 1, which represents the open sky value. The value ω can be inspected after each user action so that a user can easily see the effect of his/her action on overall light interception. At the beginning of a new growing season, ω is stored to track the history of the overall tree crown light interception, which enables better evaluation of a given training system and the capability to compare different training systems. In Figure 6A a comparison between an average of five overall tree crown light interceptions of untrained trees and trees trained as described in the previous section can be seen. In both cases the overall tree crown light interception decreases over the time due to the increasing complexity of the canopies, but in the case of untrained trees this decline is always much more pronounced. At all times the standard deviation was low and did not exceed 0.04.

Another and equally important metric for training system evaluation is light distribution through the canopy (Fig. 6B and C), which can be evaluated after the training actions in the season have been accomplished. Again we can observe in Figure 6B and C that the trained trees achieved better results at all times, which is even more obvious with increasing tree age. Both metrics together with the light intersection visualization tool can be of great help in understanding the basic principles of tree training. For more advanced users they enable the study of different training systems by comparing their effects on light interception and light distribution.

TREE VISUALIZATION REQUIREMENTS. EduAPPLE has been designed to run on an average personal computer with a dedicated graphics card where realistic looking trees can easily be generated and displayed in real-time. The test machine

Fig. 6. (A) Average tree crown light interception of five untrained and five trained apple trees toward conical shaped tree. Light interception is determined by Eq. [9] and has no units. Apple tree crown light distribution for a time period of 6 years of (B) untrained tree and (C) trained tree toward conical shape. The leaves in the canopy are classified into 10 discrete classes according to their illumination value (Eq. [3]).

Fig. 7. (A) Chronological apple tree growth without the training process at even years. (B) Generation time and number of internodes of the tree from above. Cumulative generation time represents generation time throughout the entire tree's life, while a 1-year step generation time represents the generation time between two consecutive years.

Fig. 8. Screenshot of EduAPPLE. Example shows multiple apple trees inside the high-density planting orchard.

we used contained a Core™ i7 870@2.93GHz CPU (Intel; Santa Clara, CA) and a GeForce GTX 780 GPU (NVIDIA, Santa Clara, CA).

Figure 7 demonstrates chronological tree growth without training used in the previous section. Although the trees in gardens are usually free standing, EduAPPLE can display several trees at the same time, which can be seen in Figure 8, where three rows of a high-density planting orchard can be seen. The generation times of the tree on Figure 7 show that a 1-year step generation time enables comfortable interaction with the application. In the case of multiple trees a slowdown occurs much earlier. But if trees are trained, the number of internodes increases more slowly and therefore tree generation times are still acceptable.

Discussion

The aim of our research was to develop an application that would help tree growers without access to proper education to understand the principles of training apple trees toward better light interception and light distribution through the tree crown, consequently enhancing crop yield and quality. Although profitability of this crop might not always be the primary factor, it is still important in terms of shortening food supply chains and increasing self-sufficiency in fresh fruit supply. As a result the teaching application EduAPPLE was built, where all major training techniques are supported. Its main benefit is its quick response to each training action. All tree-training techniques are easy to use and therefore no additional time for learning to use EduAPPLE is necessary. Our growth model presumes that the tree is well-watered and the tree grows without any obstacles. Because the shortage of important data, no flowering and fruiting are supported in the model, although reproductive and vegetative growth are strongly interconnected. Therefore, the vegetative growth vigor is higher and the need for tree crown manipulation is more prominent. Other than that all important apple tree phytomorphology data are included in our growth model; therefore, the response to user actions of removing or bending branches is true to the results documented in the literature. All user actions are

displayed in real-time while the tree response can only be seen in the next growing season and is generated automatically. Through branch positioning and pruning, the user can train the tree toward the desired shape in a very short time. Therefore, he/she can try to combine several tree-training techniques to better understand the effect the given techniques have on the resulting tree shape. The consequences of improper cuts and branch positioning are displayed instantly along with light interception, demonstrating the importance of growing forms.

EduAPPLE monitors user actions to offer assistance with more complex procedures. With its metrics for overall tree crown light interception and light distribution, it allows knowledge about tree training toward better yield and quality to be gathered efficiently by enabling a comparison of different training systems. As such it can also be used as a teaching tool of basic tree training techniques for horticulture students. It can lower teaching costs as there is no need to make changes to real trees. In that case it would be useful to include tree-training techniques for high-density planting orchards as well. The EduAPPLE is already designed in such a way to display multiple trees at a time (Fig. 8) with enough computer power left to apply necessary adjustments.

However, to provide more detailed tree training knowledge, EduAPPLE should enable the user to select among different rootstocks, cultivars, and predefined climate data, which would enable the inclusion of a fruiting model and evaluation of tree training techniques for both yield quality and quantity. This remains our work for the future.

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