Methods for Quantitatively Describing Tree Crown Profiles of Loblolly Pine (Pinus taeda L.)

by

Paul F. Doruska

Dissertation submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Forestry

APPROVED:

Harold E. Burkhart, Chairman
James A. Burger
Timothy G. Gregoire
Richard G. Oderwald
Marion R. Reynolds Jr.

Blacksburg, Virginia

Keywords: Nonparametric regression, Kernel, Local linear, Local polynomial, Bandwidth

Copyright 1998, Paul F. Doruska
Physiological process models, productivity studies, and wildlife abundance studies all require accurate representations of tree crowns. In the past, geometric shapes or flexible mathematical equations approximating geometric shapes were used to represent crown profiles. Crown profile of loblolly pine (*Pinus taeda* L.) was described using single-regressor, nonparametric regression analysis in an effort to improve crown representations. The resulting profiles were compared to more traditional representations. Nonparametric regression may be applicable when an underlying parametric model cannot be identified. The modeler does not specify a functional form. Rather, a data-driven technique is used to determine the shape a curve. The modeler determines the amount of local curvature to be depicted in the curve. A class of local-polynomial estimators which contains the popular kernel estimator as a special case was investigated. Kernel regression appears to fit closely to the interior data points but often possesses bias problems at the boundaries of the data, a feature less exhibited by local linear or local quadratic regression. When using nonparametric regression, decisions must be made regarding polynomial order and bandwidth. Such decisions depend on the presence of local curvature, desired degree of smoothing, and, for bandwidth in particular, the minimization of some global error criterion. In the present study, a penalized PRESS
criterion (PRESS*) was selected as the global error criterion. When individual-tree, crown profile data are available, the technique of nonparametric regression appears capable of capturing more of the tree to tree variation in crown shape than multiple linear regression and other published functional forms. Thus, modelers should consider the use of nonparametric regression when describing crown profiles as well as in any regression situation where traditional techniques perform unsatisfactorily or fail.
Acknowledgments

I wish to sincerely thank my advisor, Dr. Harold Burkhart, for his guidance, support, and especially patience throughout my graduate education in the Department of Forestry at Virginia Polytechnic Institute and State University. It was truly a circuitous route to the completion of this dissertation. I also wish to thank the members of my advisory and examination committees, namely Dr. Gregory Buhyoff, Dr. James Burger, Dr. Timothy Gregoire, Dr. Richard Oderwald, and Dr. Marion Reynolds for taking time from their busy schedules to assist me in this discourse. Special thanks also go to Dr. James Mays for providing some of the programming used in this research as well as for his clear and concise descriptions of the major topic of this effort.

The Loblolly Pine Growth and Yield Research Cooperative at Virginia Tech provided the financial assistance for this endeavor, and for that I am quite thankful. The US Forest Service Southern Global Change Program also provided much appreciated financial support at the onset of this project.

I am eternally grateful to the faculty, staff, and students in the Department of Forestry, the College of Forestry and Wildlife Resources, and the Department of Statistics for providing what I consider to be one of the best environments a graduate student could ever expect. Virginia Tech is a special place, and sometimes it takes some time away from this institution to truly appreciate it.
Table of contents

Chapter 1: Introduction and objectives ............................................... 1

1.1 Introduction ................................................................. 1
1.2 Objectives and approach ...................................................... 5
1.3 Variable definition and notation .............................................. 6

Chapter 2: Background and importance of crown shape/profile modeling ...... 7

2.1 Introduction ................................................................. 7
2.2 Crown structure ............................................................ 7
  2.2.1 Wood quality .............................................................. 8
  2.2.2 Quantification of the crown ............................................ 9
2.3 Physiological impacts of crown shape ....................................... 10
2.4 Representations of crown shape ............................................. 11
  2.4.1 Geometric shapes ........................................................ 11
  2.4.2 Fractals ................................................................. 12
  2.4.3 Structural models ....................................................... 13
  2.4.4 Mathematical equations ............................................. 14
  2.4.5 Inclusion of stochasticity ............................................. 17

Chapter 3: Nonparametric regression analysis ...................................... 18

3.1 Introduction ................................................................. 18
3.2 Kernel regression ........................................................... 19
3.3 Local polynomial regression ................................................. 22
3.4 Bandwidth choice ........................................................... 25
3.5 Variance of prediction ....................................................... 28

Chapter 4: Data, results, and conclusions .......................................... 29

4.1 Data ................................................................. 29
4.2 Nonparametric regression and bandwidth determination .................... 31
4.3 Nonparametric regression versus linear regression ............................ 40
  4.3.1 Results ................................................................. 40
  4.3.2 Summary ............................................................... 47
4.4 Nonparametric regression versus other outer crown profile models .......... 47
  4.4.1 Results ................................................................. 47
  4.4.2 Summary ............................................................... 49
4.5 Nonparametric regression versus other inner crown profile models ......... 49
4.5.1 Results ................................................................. 49
4.5.2 Summary ............................................................. 51
4.6 Optimal nonparametric models of outer and inner crown profiles .......... 51
  4.6.1 Results ................................................................. 51
  4.6.2 Summary ............................................................. 52
4.7 Discussion and conclusions .................................................. 52

Chapter 5: Summary and recommendations ............................................. 112

  5.1 Summary ................................................................. 112
  5.2 Recommendations .......................................................... 114

Literature cited ................................................................. 117

Appendix ................................................................. 125

Vita ................................................................. 129
List of tables

Table 4.1: Descriptive statistics of the 34 trees used to describe crown profiles.  30

Table 4.2: A comparison of fit criteria for varying bandwidth fits for kernel, local linear, and local quadratic regression for the two trees depicted throughout Figure 4.1. .................................................. 32

Table 4.3: A comparison of optimal (PRESS* criterion) nonparametric fits for the six trees depicted in Figure 4.2. ................................................. 34

Table 4.4: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.3. .................................................. 35

Table 4.5: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.4. .................................................. 35

Table 4.6: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.5. .................................................. 36

Table 4.7: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.6. .................................................. 36

Table 4.8: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.7. .................................................. 37

Table 4.9: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.8. .................................................. 37

Table 4.10: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.9. .................................................. 38

Table 4.11: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the four trees depicted in Figure 4.10. .................................................. 38
Table 4.12: A comparison of fit criteria for optimal (via PRESS*) bandwidth fits for kernel, local linear, and local quadratic regression for the two trees depicted in Figure 4.11. ................................................................. 39

Table 4.13: Fit statistics for the curves depicted in Figure 4.12. ......................... 41

Table 4.14: Fit statistics for the curves depicted in Figure 4.13. ......................... 41

Table 4.15: Fit statistics for the curves depicted in Figure 4.14. ......................... 42

Table 4.16: Fit statistics for the curves depicted in Figure 4.15. ......................... 42

Table 4.17: Fit statistics for the curves depicted in Figure 4.16. ......................... 43

Table 4.18: Fit statistics for the curves depicted in Figure 4.17. ......................... 43

Table 4.19: Fit statistics for the curves depicted in Figure 4.18. ......................... 44

Table 4.20: Fit statistics for the curves depicted in Figure 4.19. ......................... 44

Table 4.21: Fit statistics for the curves depicted in Figure 4.20. ......................... 45

Table 4.22: A comparison of absolute residuals of the outer crown profile fits using optimal nonparametric regression, simple linear regression, and multiple linear (quadratic and cubic) regression. ...................... 46

Table 4.23: A comparison of absolute residuals of the outer crown profile fits using optimal nonparametric regression and the Mohren model, and the application of the Baldwin model. ................................. 48

Table 4.24: A comparison of absolute residuals of the inner crown profile fits using optimal nonparametric regression and the application of the Baldwin model. .......................................................... 50

Table A3.1: Dataset used to illustrate changing weights with changing bandwidths in kernel regression. ................................................................. 126

Table A3.2: Weight matrix used to obtain a kernel regression fit to the data shown in Table A3.1 using a bandwidth=0.50. .............................................. 126

Table A3.3: Weight matrix used to obtain a kernel regression fit to the data shown in Table A3.1 using a bandwidth=0.25. .............................................. 127

Table A3.4: Weight matrix used to obtain a kernel regression fit to the data shown in Table A3.1 using a bandwidth=0.10. .............................................. 127
List of figures

Figure 4.1: A comparison of varying bandwidth nonparametric fits to two crown profiles. (a), (c), and (e): tree 10701; (b), (d), and (f): tree 20301. 57

Figure 4.2: A comparison of optimal (PRESS* criterion) nonparametric fits to six crown profiles. (a) tree 10701 (b) tree 20301 (c) tree 20401 (d) tree 20401 (e) tree 10501 (f) tree 10301. … 58

Figure 4.3: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 10101 (b) tree 10102 (c) tree 10103 (d) tree 10201. ………………… 59

Figure 4.4: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 10301 (b) tree 10302 (c) tree 10303 (d) tree 10401. ………………… 60

Figure 4.5: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 10501 (b) tree 10601 (c) tree 10701 (d) tree 10801. ………………… 61

Figure 4.6: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 10901 (b) tree 10902 (c) tree 20101 (d) tree 20201. ………………… 62

Figure 4.7: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 20301 (b) tree 20401 (c) tree 20501 (d) tree 20601. ………………… 63

Figure 4.8: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 20701 (b) tree 20801 (c) tree 20901 (d) tree 30101. ………………… 64

Figure 4.9: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 30201 (b) tree 30301 (c) tree 30401 (d) tree 30501. ………………… 65

Figure 4.10: Optimal (PRESS* criterion) nonparametric regression fits to four crown profiles: (a) tree 30601 (b) tree 30701 (c) tree 30801 (d) tree 30901. ………………… 66

Figure 4.11: Optimal (PRESS* criterion) nonparametric regression fits to two crown profiles: (a) tree 31001 (b) tree 31101. ………………… 67
Figure 4.12: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 10101 (b) tree 10102 (c) tree 10103 (d) tree 10201. ........ 68

Figure 4.13: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 10301 (b) tree 10302 (c) tree 10303 (d) tree 10401. ........ 69

Figure 4.14: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 10501 (b) tree 10601 (c) tree 10701 (d) tree 10801. ........ 70

Figure 4.15: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 10901 (b) tree 10902 (c) tree 20101 (d) tree 20201. ........ 71

Figure 4.16: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 20301 (b) tree 20401 (c) tree 20501 (d) tree 20601. ........ 72

Figure 4.17: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 20701 (b) tree 20801 (c) tree 20901 (d) tree 30101. ........ 73

Figure 4.18: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 30201 (b) tree 30301 (c) tree 30401 (d) tree 30501. ........ 74

Figure 4.19: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for four trees: (a) tree 30601 (b) tree 30701 (c) tree 30801 (d) tree 30901. ........ 75

Figure 4.20: Optimal (PRESS* criterion) nonparametric regression fits compared to simple linear regression, and multiple linear (quadratic and cubic) regression for two trees: (a) tree 31001 (b) tree 31101. ........ 76
Figure 4.21: Optimal (PRESS* criterion) nonparametric regression residuals versus relative crown height for all trees. .............................. 77
Figure 4.22: Simple linear regression residuals versus relative crown height for all trees. ........................................................................................................ 78
Figure 4.23: Multiple linear (quadratic) regression residuals versus relative crown height for all trees. ................................................................. 79
Figure 4.24: Multiple linear (cubic) regression residuals versus relative crown height for all trees. ................................................................. 80
Figure 4.25: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 10101 (b) tree 10102 (c) tree 10103 (d) tree 10201. .... 81
Figure 4.26: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 10301 (b) tree 10302 (c) tree 10303 (d) tree 10401. .... 82
Figure 4.27: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 10501 (b) tree 10601 (c) tree 10701 (d) tree 10801. .... 83
Figure 4.28: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 10901 (b) tree 10902 (c) tree 20101 (d) tree 20201. .... 84
Figure 4.29: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 20301 (b) tree 20401 (c) tree 20501 (d) tree 20601. .... 85
Figure 4.30: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 20701 (b) tree 20801 (c) tree 20901 (d) tree 30101. .... 86
Figure 4.31: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 30201 (b) tree 30301 (c) tree 30401 (d) tree 30501. .... 87
Figure 4.32: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for four trees:
(a) tree 30601 (b) tree 30701 (c) tree 30801 (d) tree 30901. .... 88
Figure 4.33: Optimal (PRESS* criterion) nonparametric regression fits compared to the Baldwin and Mohren models for two trees:
(a) tree 31001  (b) tree 31101. 89

Figure 4.34: Baldwin model residuals versus relative crown height for all trees. 90

Figure 4.35: Mohren model residuals versus relative crown height for all trees. 91

Figure 4.36: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 10101  (b) tree 10102  (c) tree 10103  (d) tree 10201. 92

Figure 4.37: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 10301  (b) tree 10302  (c) tree 10303  (d) tree 10401. 93

Figure 4.38: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 10501  (b) tree 10601  (c) tree 10701  (d) tree 10801. 94

Figure 4.39: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 10901  (b) tree 10902  (c) tree 20101  (d) tree 20201. 95

Figure 4.40: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 20301  (b) tree 20401  (c) tree 20501  (d) tree 20601. 96

Figure 4.41: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 20701  (b) tree 20801  (c) tree 20901  (d) tree 30101. 97

Figure 4.42: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 30201  (b) tree 30301  (c) tree 30401  (d) tree 30501. 98

Figure 4.43: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for four trees:
(a) tree 30601  (b) tree 30701  (c) tree 30801  (d) tree 30901. 99

Figure 4.44: Optimal (PRESS* criterion) nonparametric regression fits to inner crown radius compared to the Baldwin model for two trees:
(a) tree 31001  (b) tree 31101. 100
Figure 4.45: Optimal (PRESS* criterion) nonparametric regression residuals from inner crown profile fits versus relative crown height for all trees. 101

Figure 4.46: Baldwin model residuals from inner crown profile fits versus relative crown height for all trees. ................................................................. 102

Figure 4.47: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 10101  (b) tree 10102  (c) tree 10103  (d) tree 10201. .... 103

Figure 4.48: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 10301  (b) tree 10302  (c) tree 10303  (d) tree 10401. .... 104

Figure 4.49: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 10501  (b) tree 10601  (c) tree 10701  (d) tree 10801. .... 105

Figure 4.50: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 10901  (b) tree 10902  (c) tree 20101  (d) tree 20201. .... 106

Figure 4.51: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 20301  (b) tree 20401  (c) tree 20501  (d) tree 20601. .... 107

Figure 4.52: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 20701  (b) tree 20801  (c) tree 20901  (d) tree 30101. .... 108

Figure 4.53: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 30201  (b) tree 30301  (c) tree 30401  (d) tree 30501. .... 109

Figure 4.54: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for four trees:
(a) tree 30601  (b) tree 30701  (c) tree 30801  (d) tree 30901. .... 110

Figure 4.55: Optimal (PRESS* criterion) nonparametric regression fits to outer and inner crown profiles for two trees:
(a) tree 31001  (b) tree 31101. ................................. 111